142733

MATHEMATICAL MODELING ESTIMATE OF ENVIRONMENTAL EXPOSURE DUE TO PCB-CONTAMINATED HARBOR SEDIMENTS OF WAUKEGAN HARBOR AND NORTH DITCH

By:

Robert V. Thomann
Michael T. Kontaxis

HydroQual, Inc.
Mahwah, New Jersey 07430

Contract No. 68-03-2568
Task No. 7010

Project Officer

Ivars Licis

United States Environmental Protection Agency
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

February 1981

PREFACE

The U.S. Environmental Protection Agency has initiated legal action against the Outboard Marine Corporation (OMC) located adjacent to Waukegan Harbor, Waukegan, Illinois. This industry has apparently discharged PCB-contaminated effluents both to a Ditch tributary to Lake Michigan and to the Harbor itself over a period of approximately 20 years. This report presents the results of a study undertaken to provide EPA with technical support for this litigation.

The study included an evaluation of data to determine the amount and distribution of PCB in contaminated sediments, an evaluation of PCB resuspension in the Harbor and Ditch, estimation of the quantity of PCB being discharged from the Harbor and Ditch to Lake Michigan and a determination of the environmental impact and significance of the resuspended PCB upon the Harbor and the Lake. Additionally, an assessment of the significance of the removal of Harbor sediments is provided.

Technical work which forms the basis of this report commenced in May 1979 and was conducted at the offices of Hydroscience, Inc., Westwood, New Jersey. Mr. John J. Higgins participated in the development of the technical work at that time. Subsequent to May, 1980, additional technical evaluations were performed and the final report was prepared by HydroQual, Inc., Mahwah, New Jersey, under subcontract.

ABSTRACT

This study was undertaken to provide USEPA with technical support for legal action taken against an industry accused of contaminating sediments in the North Ditch and Waukegan Harbor, Illinois. In support of this litigation, quantitative evaluations of the extent of the PCB exposure currently presented by this condition to the Lake Michigan and Harbor ecosystems were made.

The "best estimate" of how much PCB is contained in the North Ditch and Harbor sediments is 484,500 kg. Given the uncertainity associated with the estimates of the mass of PCB discharged, it cannot be determined from the data alone whether all the PCB discharged is still in the Ditch/Harbor system or if thousands of kilograms of PCB are unaccounted for and have presumably escaped from the Ditch/Harbor system.

A mathematical model of the Harbor was prepared and calibrated to chloride, suspended solids, dye and PCB data. The model indicates that, presently, about 10 kg/yr of PCB is reaching the Lake from the Harbor, including transient storm events.

A mathematical model of the North Ditch was prepared and calibrated to suspended solids and PCB data. Model simulation indicate that the total PCB discharge from the North Ditch is, at present, about 5 kg/yr. The total present PCB discharge to Lake Michigan from the Harbor/Ditch system is about 15 kg/yr.

Small fish tissue levels are estimated to be ten to twenty times higher than FDA limits for fish for human consumption.

Removal of PCB contaminated sediments to the 100 µg/g level result in a calculated significant drop in fish body burdens. Removal of PCB contaminated sediment to the 10 µg/l level reduces calculated fish body burdens to almost FDA limits. Additional removal of sediment to the 1 µg/g level does not result in any further marked reductions in fish body burdens.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

SECTION 1

INTRODUCTION

Harbor

Waukegan Harbor is located on the western shore of Lake Michigan, some 48 km (30 mi.) north of Chicago and approximately 15 km (9 mi.) south of the Illinois-Wisconsin state line. The Harbor is approximately 1.5 km (.9 mi.) long in the shape of an L, running north and south. Two side channels each about 250 m (800 ft.) in length branch off to the west. Depths range from as little as 2 meters (6 feet) in the side branches to as much as 6 meters (20 feet) in the navigation channels. Figure 1 shows the location of Waukegan Harbor.

The Harbor drains an area of 390,000 sq.m. (96 acres). Its shores are lined with industrial and commercial facilities. Total discharges to the Harbor are estimated to be approximately 0.25×10^3 m^3/day (1 MGD) from both runoff and industrial sources. It is also estimated that about 0.75×10^3 m^3/day (3 MGD) are withdrawn from the Harbor by the surrounding industrial facilities.

Since the contamination of the Harbor by PCB's has been identified, numerous sampling programs have been conducted. A station identification system has been established and is adhered to in this report. The locations of the Harbor and near-shore Lake Michigan sampling stations are shown on Figure 2.

Ditch

The North Ditch is a small tributary to Lake Michigan located to the Northeast of the City of Waukegan and drains a small area (.11 mi^2) of mostly industrial coverage, Figure 3A. The geomorphology and hydrology of the North Ditch has been investigated only recently (Noehre and Graf, 1980) (ENCOTEC, 1977) (Battelle, undated), and then only in connection with the PCB contamination issue. The flow and depth of water in the North Ditch is governed by rainfall, groundwater and the water level in Lake Michigan. The adverse slope of the bed in the last 500-800 ft., (Figure 3B), causes backwater conditions even with minimal wind action, whereas at higher onshore winds the lake water intrudes into the North Ditch which is subsequently cut off from the lake by the formation of sandbars at the mouth. These sandbars are subsequently removed naturally or by intervention of man.

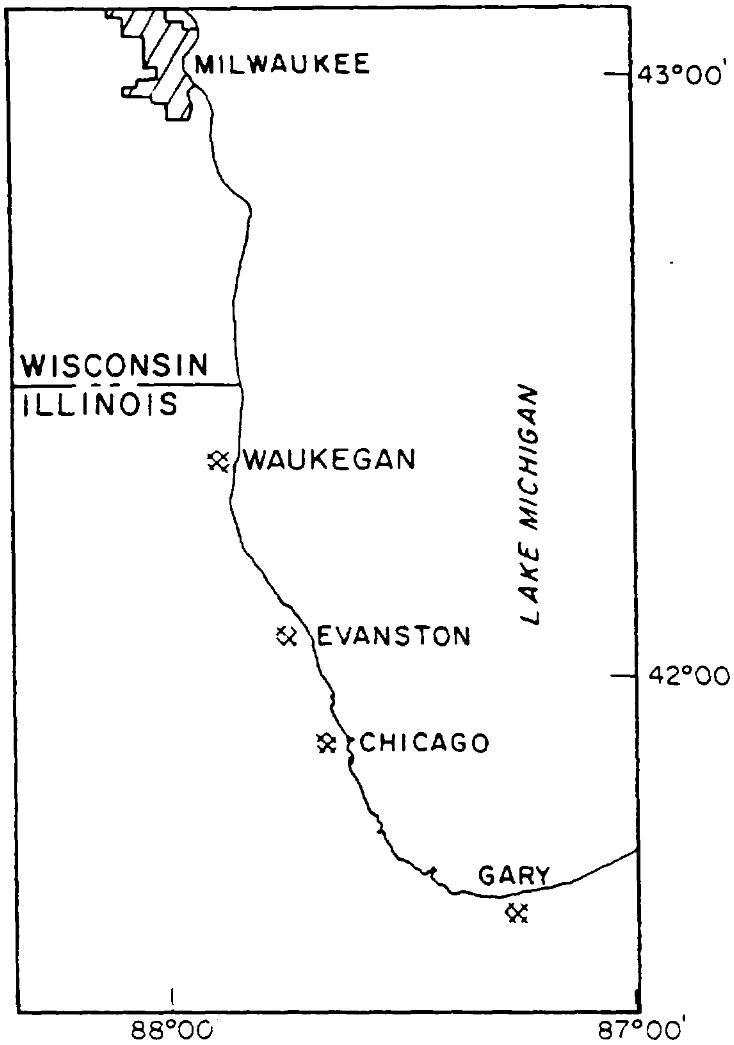


Figure 1. Location of study area

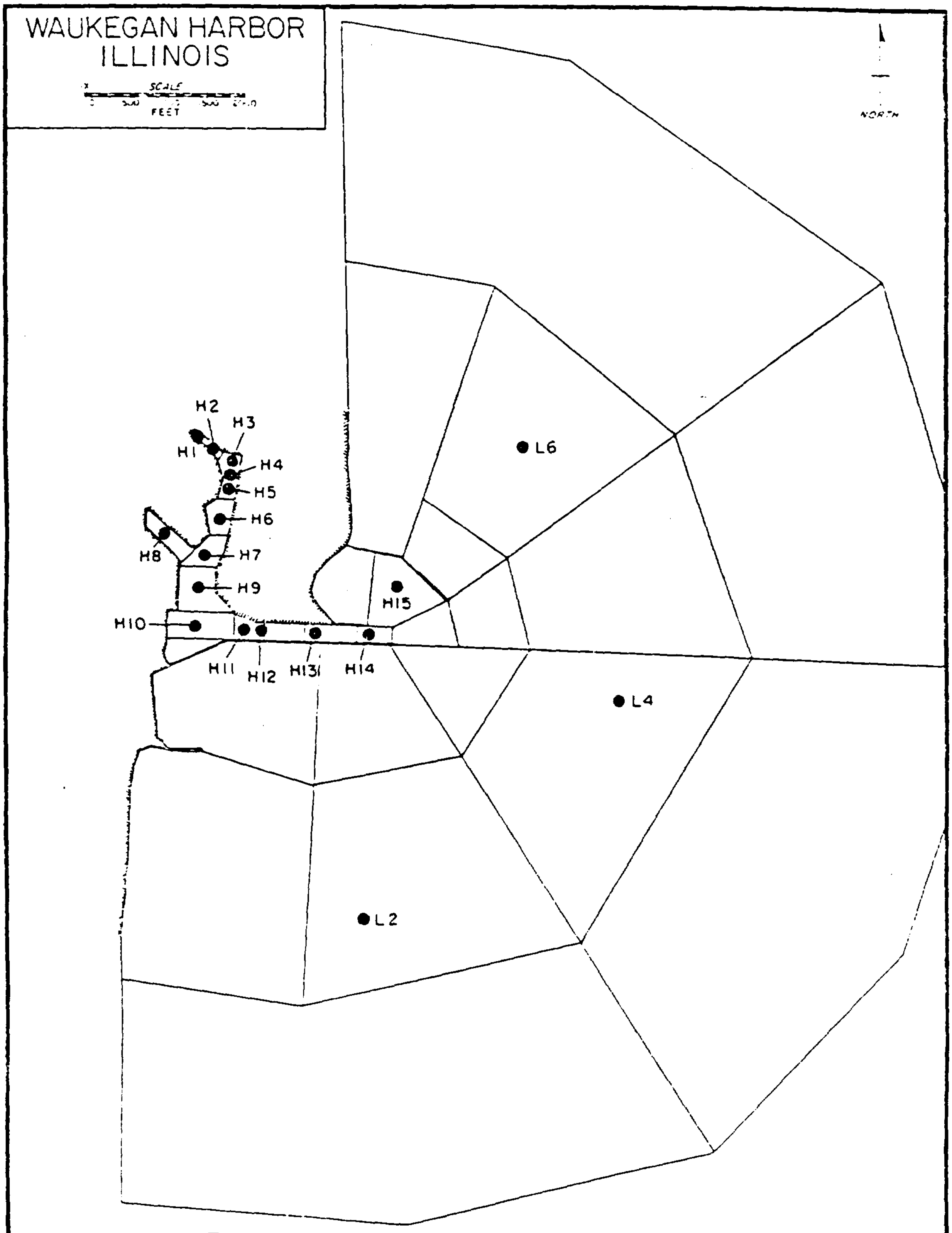


Figure 2. Sampling station locations

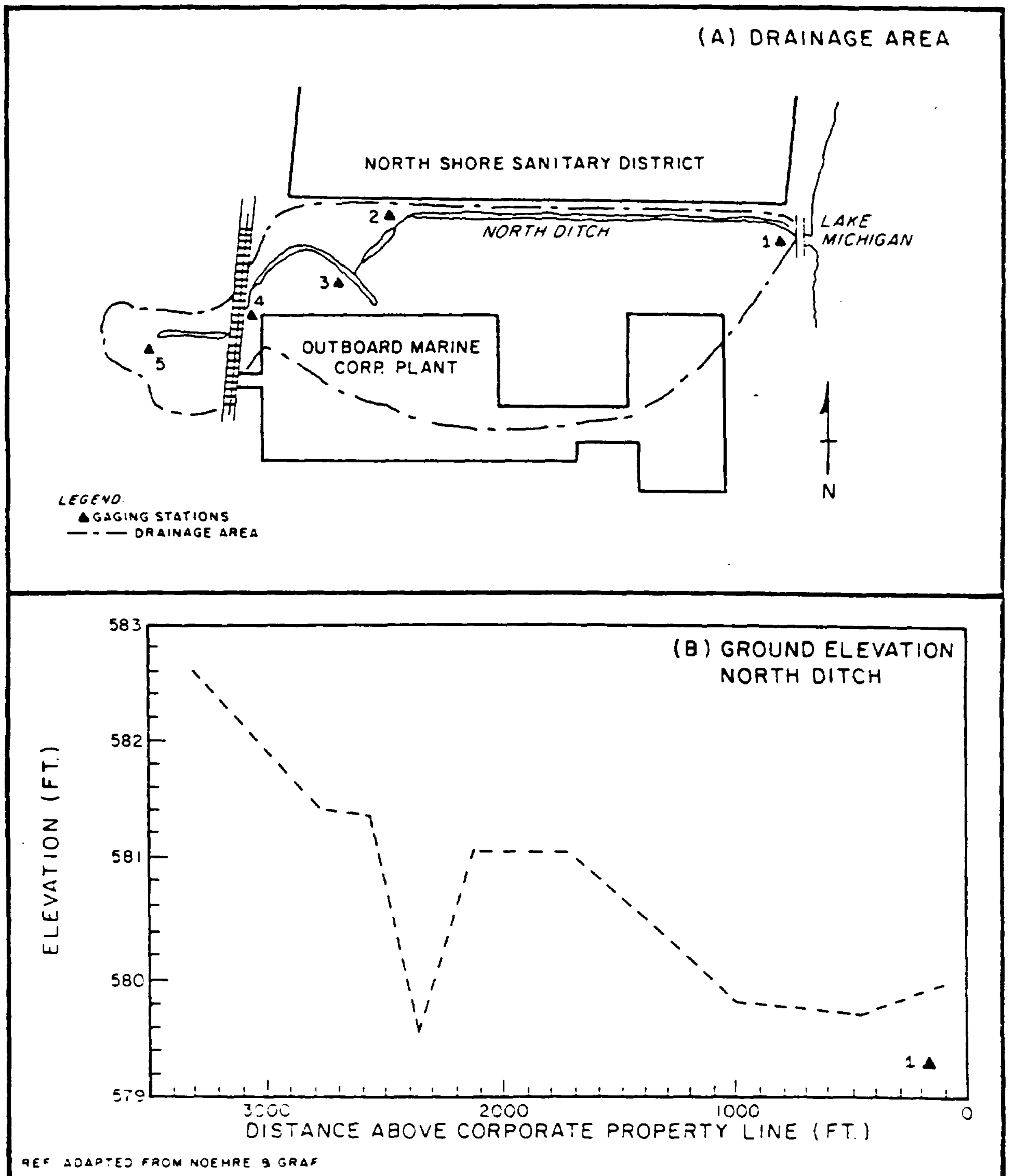


Figure 3. Location and general features of the North Ditch

SECTION 2

CONCLUSIONS

The following general conclusions are drawn from the work presented in this Report.

1. (a) The "best estimate" of the mass of PCB residing in the sediments of Waukegan Harbor and the North Ditch is 484,500 kg (1,100,000 lbs). About 43% of this mass is in Waukegan Harbor and about 95% of the mass in the Harbor is contained in Slip # 3.

   (b) The data on PCB in the sediment are quite variable and based on statistical procedures, the "high estimate" of the mass is 871,000 kg (1,900,000 lbs) and the "low estimate" is 125,500 kg (276,600 lbs).

   (c) One cannot judge on the basis of these estimates alone whether there has been or whether there is now any significant discharge of PCB from the Harbor-Ditch system. The mass of PCB in the sediment must be coupled to additional analyses of the hydrographic behaviour of the Harbor and Ditch waters and suspended sediment.

2. (a) Present total PCB concentrations in the water column vary from about 0.6 μg/l in the inner Harbor to less than .01 μg/l in the Lake region directly offshore from the Harbor. The range of variability in the water column concentrations is about 1.5-2 orders of magnitude.

   (b) About 60% of the total Harbor PCB in the water column is in the dissolved form. The percent of the dissolved form decreases to about 40% in the Lake.

   (c) For the North Ditch, data obtained in 1979 indicate average water column PCB concentrations of about 7 μg/l with peak values during rainfall events of 80-160 μg/l. During a rainfall on March 30, 1979, about .14 kg (0.3 lb) were discharged to the Lake.

3. (a) A mathematical model of the Harbor, calibrated to chloride, suspended solids and dye data indicates an approximate horizontal exchange across the Harbor-Lake boundary equivalent to a flow of about 3.9 m^3/s (140 ft^3/s). This exchange flow is due to

the natural process of water movement between the Harbor and Lake. The model was calibrated to the PCB data in the water column using existing PCB sediment concentrations as the primary input.

(b) A mathematical model of suspended solids and PCB transfer in the North Ditch, constructed with principles similar to that of the Harbor were calibrated to data collected in 1979 and indicated that transient storm events can result in the transient discharge of PCB due to resuspension from contaminated North Ditch sediment.

4. (a) At present, the calculations indicate that the net exchange of PCB from the Harbor to the Lake is about 10 kg/yr (22 lb/yr), including transient storm events.

(b) For the North Ditch, an average discharge of about 2 kg/yr (4.4 lb/yr) is estimated based on both observed data for 1979 and model calibrations. A simulation of a single storm event equivalent to the maximum expected event in an average year resulted in the discharge of an additional approximate load of 3 kg (7 lbs). The total discharge from the North Ditch is about 5 kg/yr (11 lb/yr).

(c) The total present discharge to Lake Michigan from the Harbor/Ditch system is therefore about 15 kg/yr.

5. Under the present level of dissolved PCB in the Harbor, small (<300 mm) fish tissue levels are estimated to be five to ten times higher than FDA limits for fish for human consumptionof 5 μg/g in the edible portion.

6. (a) It is estimated that during direct discharge of PCB to the Harbor (about 1955-1971), 38% of the discharge load escaped to the Lake and 62% entered the sediment.

(b) For the North Ditch, during low flow, low scour conditions, it is estimated that 29% of PCB discharged to the Ditch (about 1955-1971) escaped to the Lake and 71% entered the North Ditch sediment. Under higher flow and higher scour conditions, about 50% of the discharged PCB entered the Lake.

7. (a) During the period 1955-1971, 5,300,000 kg of PCB were purchased by Outboard Marine Corporation. On the basis of the mass of PCB presently in the

Harbor/Ditch sediments and the estimated fraction of any PCB discharged to the Harbor/Ditch that enters the Lake, it is calculated that during the use of PCB by CMC, 14% of the purchased PCB entered the Harbor/Ditch complex under the "best estimate." The range is from 4% to 24%.

(b) It is also calculated that during the use of PCB, 5% of the total amount purchased escaped to Lake Michigan using the "best estimate." The low and high estimate is 1-7%. The 5% loss of purchased PCB to Lake Michigan represents an average annual input to the Lake of 15,000 kg/yr (33,000 lb/yr). The range in the average annual input is from 4,200 kg/yr (9,200 lb/yr) to 26,600 kg/yr (58,600 lb/yr).

(c) The "best estimate" of 15,000 kg/yr discharged to lake Michigan during PCB product usage is at least 100-1000 times greater than the present estimated discharge of 10-20 kg/yr.

8. (a) Relative to the whole of Lake Michigan, the present flux from Waukegan Harbor and the North Ditch of about 10-20 kg PCB/yr is less than 1-2% of the total present load of 1400-5600 kg PCB/yr. The present flux is more significant however on a local near-shore basis where regions of fish PCB concentrations greater than 5 μg/g are estimated.

(b) The past discharge during the time of PCB usage may have ranged from 3-5 times the present PCB input from all other external sources. It is estimated that the 15 years of input at 15,000 kg/yr resulted in a total PCB concentration for Lake Michigan of 7-15 ng/l in 1970.

(c) The past discharge of PCB to the Lake from the Harbor and Ditch during use of PCB may have accounted for approximately 50-90% of Lake Michigan water concentration and fish body burden at peak levels.

9. (a) Calculations indicate that dredging of contaminated Waukegan Harbor sediment to levels of approximately 10-100 μg/g would probably eliminate the present discharge of PCB from the Harbor to the Lake.

(b) Removal of PCB-contaminated sediment to 100 μg/g results in a calculated significant drop in fish body burdens to less than 5 μg/g for all but the innermost 500 m of the Harbor.

(c) Removal of PCB-contaminated sediment to 10 μg/g is estimated to result in fish body burdens in the Harbor to levels of about 3 μg/g.

(d) Additional removal of PCB-contaminated sediment to 1 μg/g does not result in marked improvement in water quality or any further marked reductions in fish body burdens.

SECTION 3

HARBOR AND NORTH DITCH SEDIMENT PCB

A critical determination of the problem at hand is to estimate the amount of PCB in the sediments of the Waukegan Harbor and North Ditch. This determination is made by an examination and statistical analysis of the available PCB sediment concentrations. Since the method for estimating the PCB mass is the same for both the Harbor and the Ditch, the available data are discussed first and the method and the resulting estimates are given. Particular emphasis is placed on the sediment since the solids in the bed of the Harbor and Ditch represent the principal reservoir of PCB from past discharges.

Harbor

Three principal sources (Battelle, undated; Armstrong, 1979; and ERG, 1979) provided data on concentrations of PCB in the harbor sediments. A later (1981) series of borings in slip No. 3, performed by Warzyn Engineering, are not included inthis analysis since only a small fraction of the data were available. Battelle (undated) reviewed and presented data from four surveys as follows:

U.S.E.P.A. - 5/12/76
U.S.E.P.A. - 6/9/76
State of Illinois - 2/77
ENCOTER - 5/77

The Armstrong (1977) data are for the surface sediment samples whereas the other surveys contain data on samples as far as 5 feet below the surface of the sediment.

Figure 4 is a plot of the surface sediment PCB data as a function of Harbor distance. At the innermost Harbor location (Stas. H1 and H2) values ranged from 100 to 10,000 μg PCB/g (dry). Concentrations then decrease several orders of magnitude to a range from 0.1 to 10 μg/g at the Harbor mouth. These values compare to a range of PCB surface sediment concentrations for open Lake Michigan of .01 - 0.1 μg/g (IJC, 1978). There is no apparent difference between the 1976 and 1979 data.

Figure 5 shows an example of the frequency distribution of the sediment PCB data, on the left using an arithmetic scale of concentration interval, and on the right using a log scale of PCB intervals. The latter frequency distribution appears more normally distributed and indicates the tendency for the data to

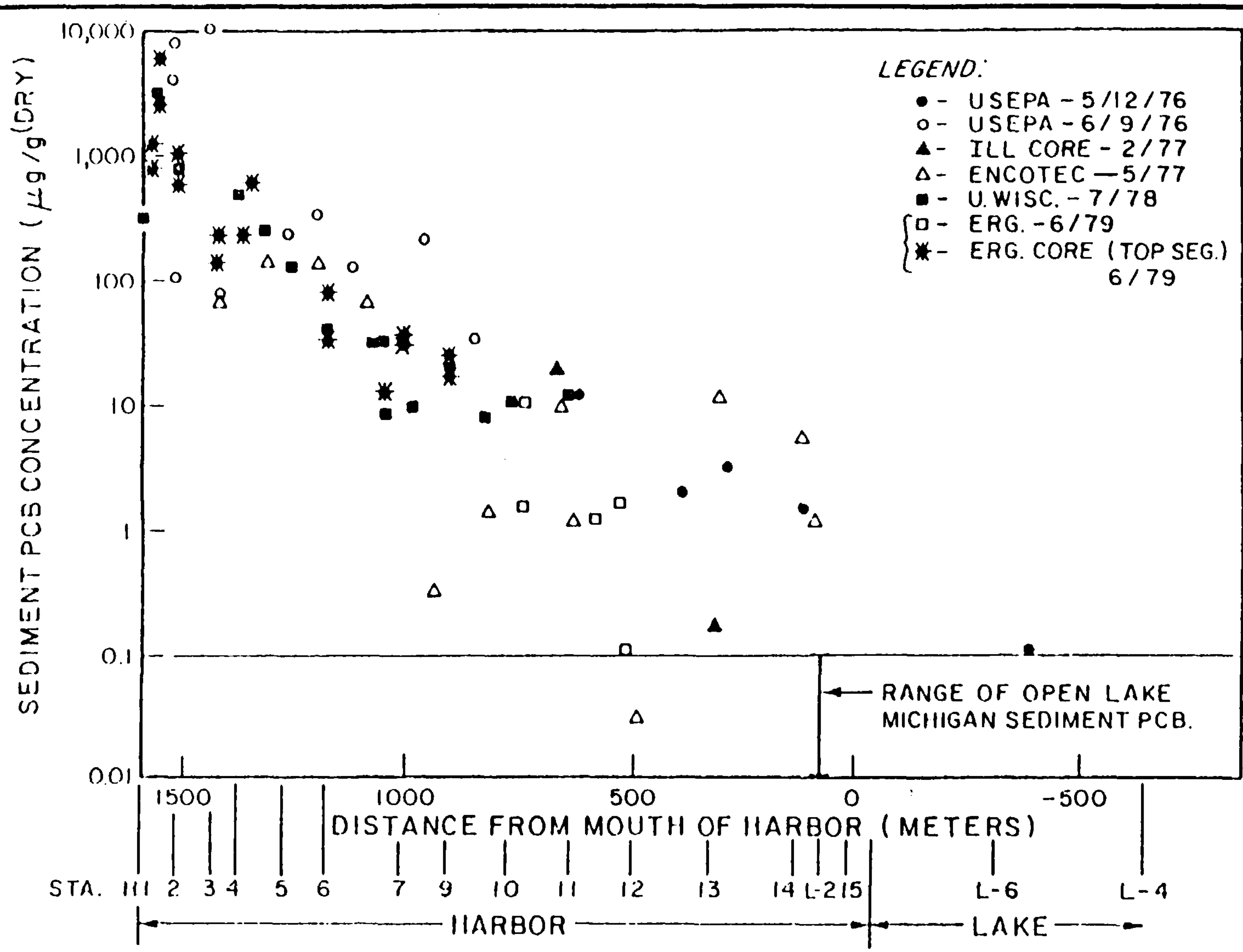
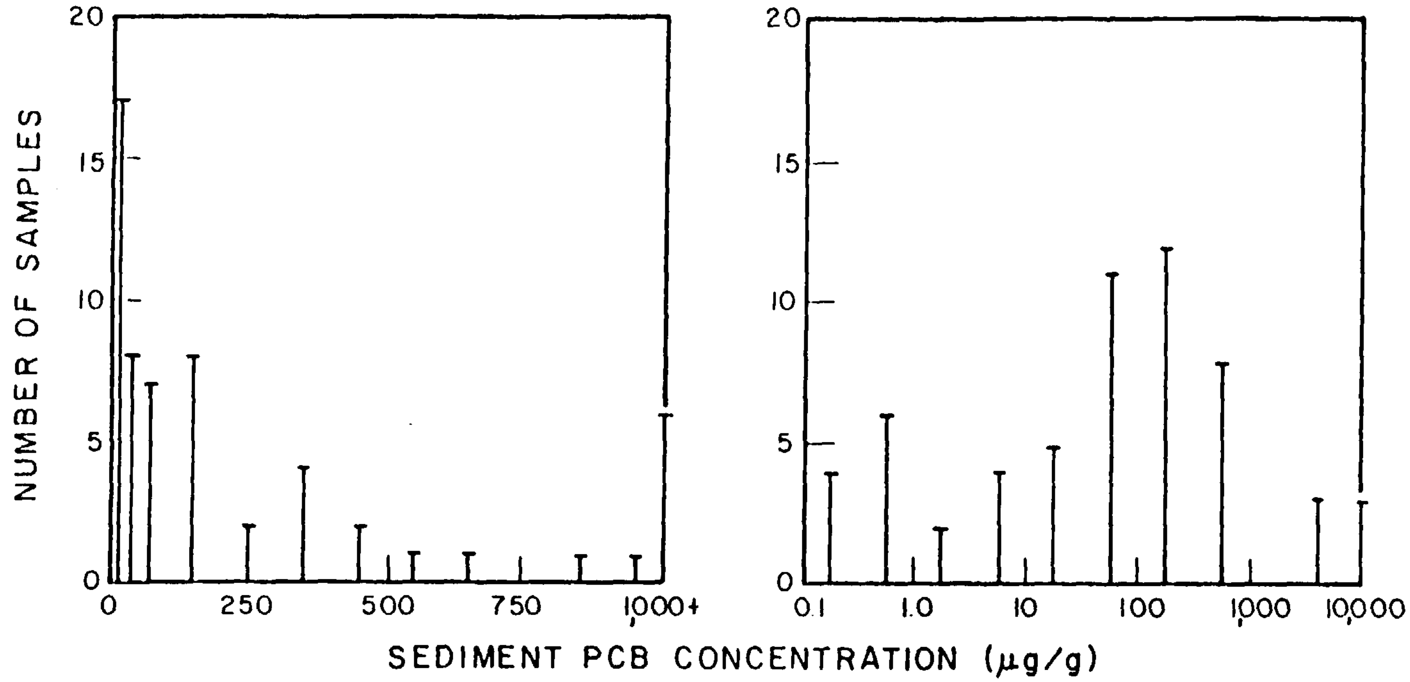


Figure 4. Surface sediment total PCB concentrations



NOTE: DOES NOT INCLUDE
ALL DATA.

Figure 5. Frequency distribution of sediment total PCB concentrations

be representative of a log normal frequency distribution. This distribution is further explored in Figure 6 where the data are plotted on log normal frequency scales. Note that over all depths to 1.5 meters (5 feet) over the entire Harbor region, the concentrations span seven orders of magnitude. As shown, the data tend to be in three groups: the high concentrations in the 0-1 meter (0-3 ft) depth in the uppermost region of the Harbor (Slip # 3, Stations H1 and H2 of Figure 2), the remainder of the Harbor sediments down to 1 meter (3 ft) and finally the deeper sediments in the 1-5 meter (3-5 ft) range. The median of all the data is 55 μg/g, with a 90% exceedance value of 2000 μg/g. The log normal distribution of sediment PCB data has also been reported by Tofflemire et al (1979) from an analysis of PCB's in the Hudson River. In Waukegan Harbor, the wide range of PCB in the sediment probably results from highly localized depositional patterns resulting in variable "hot spots" which are randomly sampled. The data variability indicates a need for additional sediment sampling and evaluation and comparison of such data to the existing distribution of concentrations.

Ditch

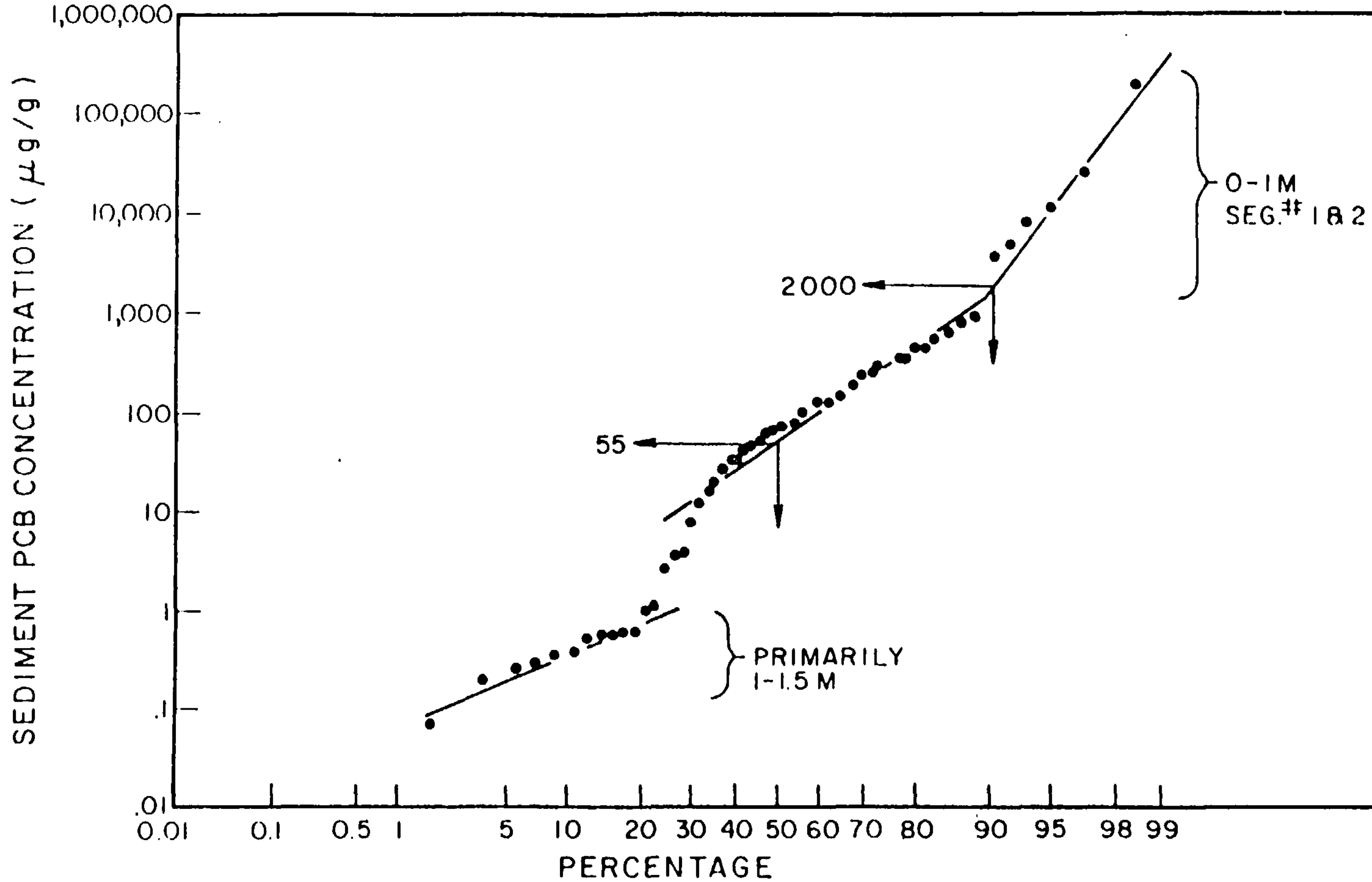
Two principal references (Battelle undated, Mason and Hanger 1981) provided data on concentrations of PCB in the sediments of the North Ditch. Battelle reviewed and presented data from four surveys as follows

USEPA 6/9/76
State of Illinois 6/9/76
State of Illinois 2/77
ENCOTEC 4/77

Figure 7 shows the areas of the sampling stations of North Ditch sediments. The most intensively sampled areas are areas 2 and 3 where the highest bottom sediment concentrations have been reported. Figure 8 shows the distribution of the data with depth at each station. From these distributions, it can be argued that the sediment "mixing" within the sediment is unequal, hence, the degree of scouring and deposition appears to be quite variable over the length of the ditch.

Method of Estimating the Sediment PCB Mass

Given a volume of PCB contaminated sediment with data on the PCB concentration (μg/g), the method consists of obtaining: (1) a "mean" or "best estimate" concentration that may be attributed to the whole volume, (2) a measure of the error or the error in the estimate, in forming the "mean" or "best estimate" in (1). The best estimate of the PCB mass and the error of the estimate in



NOTE: DOES NOT INCLUDE
ALL DATA.

Figure 6. Frequency distribution of sediment total PCB concentrations

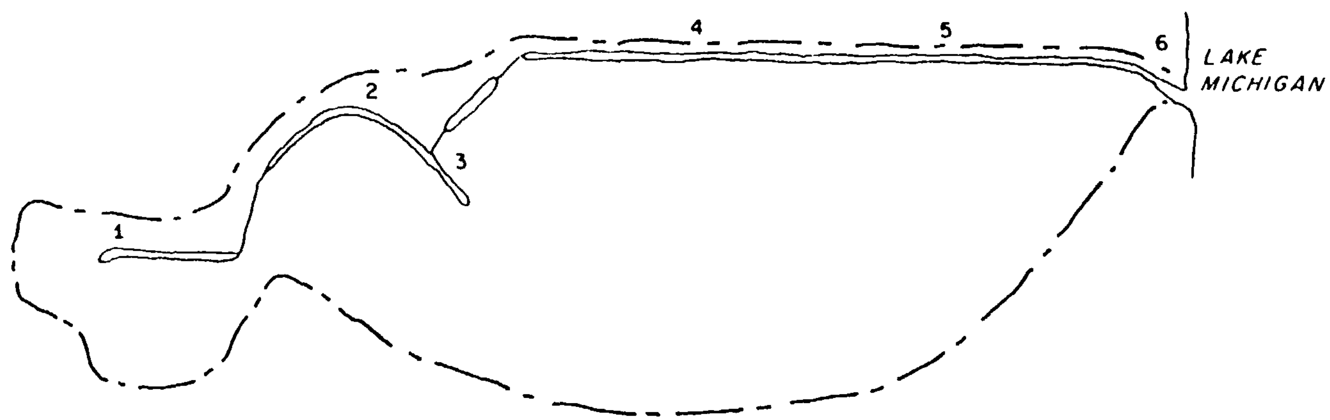


Figure 7. Location of sampling sites of North Ditch sediments

this volume of sediment is then calculated from the mass of sediment, the mean and error in the mean of the PCB concentration. The details of the procedure are described in the following example. Figure 9 shows a probability plot of the natural logarithms of the PCB concentrations in first 1 foot layer of bottom sediment in area 2 of the North Ditch. It also shows the approximate normal distribution representing the log-transformed data. From this distribution, the mean and standard deviation of the log transformed data are determined. These parameters are used to calculate the best estimate of the concentrations and the standard error in that estimate. Thus if $\{r_i\}$ are survey data, then $x_i = \ln r_i$ and the x_i data are shown in Figure 9 with mean and standard deviation $\mu_x = 9.4$ and $\sigma_x = 1.1$. The best estimate of the mean of $\{r_i\}$ data, $\hat{\mu}_r$, is calculated from (Parzen, 1960)

$$\hat{\mu}_r = \exp\{\mu_x + \frac{1}{2}\sigma_x^2\}$$

and the standard error in the estimate of μ_r is given by

$$\hat{\sigma}_{\mu_r} = \mu_x \sigma_x \{\frac{1}{N} + \frac{1}{2N}\sigma_x^2\}^{1/2}$$

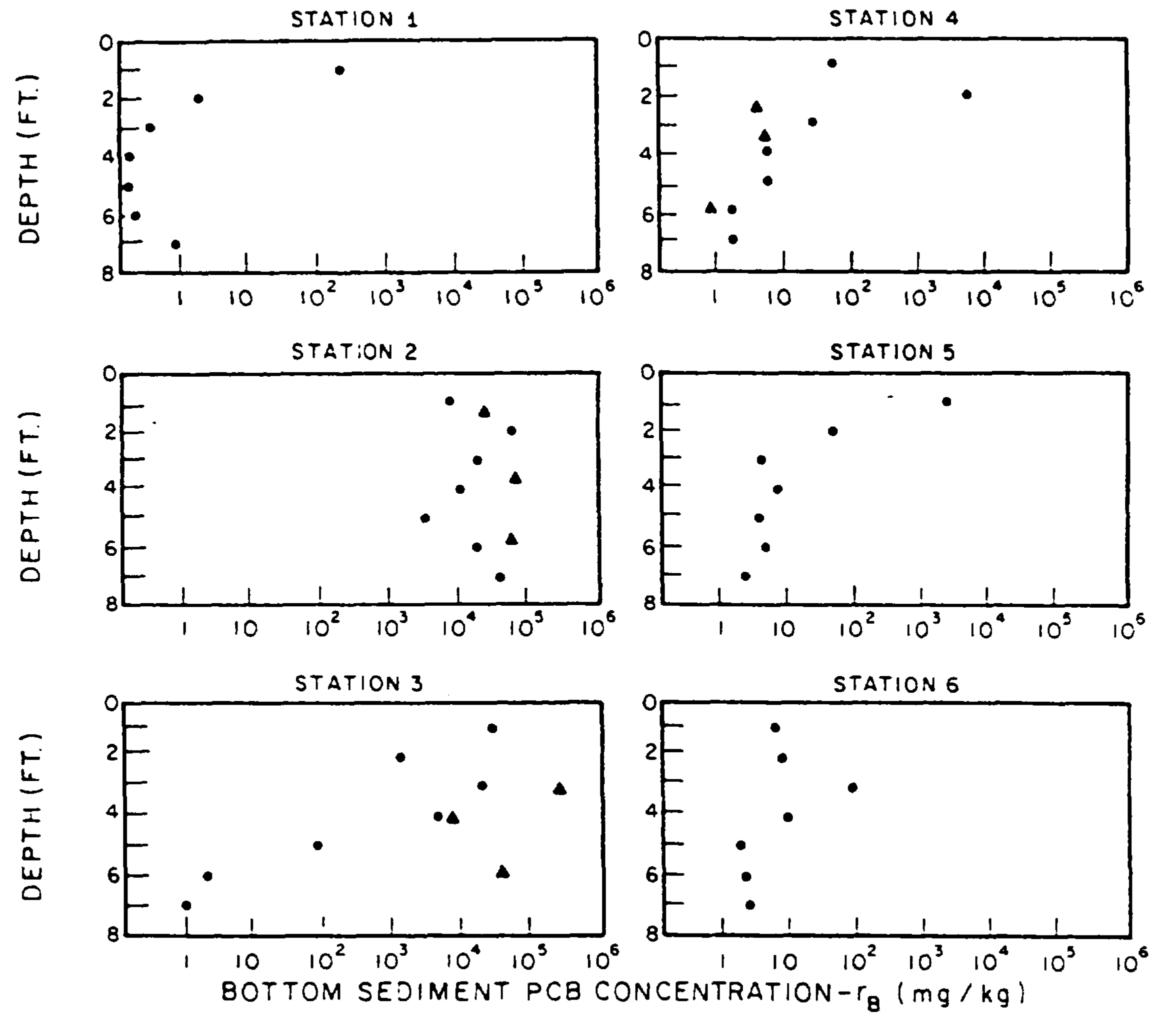
The "best," "high" and "low" estimates of the concentration are

$$\hat{\mu}_r, \quad \hat{\mu}_r + \hat{\sigma}_{\mu_r}, \quad \hat{\mu}_r - \hat{\sigma}_{\mu_r}$$

respectively.

These estimates, when multiplied, by the sediment mass in each volume, will yield the corresponding estimates of the PCB mass. It should be noted that this method depends on two key factors: (i) the number of data points within a given volume and (ii) the basis for the definition of a volume element. The first factor underlies the assumption of log normality of the data and the resulting parameter values. The second factor, represents the spatial extent attributed to a datum or a group of data. Both of these factors and especially the second one, can induce fluctuations on the estimates. When this procedure is carried out on the harbor and ditch data, the estimates are shown in Table I. For the Harbor, more than 95% of the total mass is contained in Slip # 3, the uppermost arm of the Harbor.

Figures 10 and 11 show the estimated mean of total PCB in the sediments of the harbor and the ditch respectively by depth across each of the water bodies.



LEGEND
- • ENCOTEC 4/77
- ▲ MASON & HANGER, 1980

NOTE: DOES NOT INCLUDE ALL DATA.

Figure 8. Sediment PCB concentrations at six sampling stations

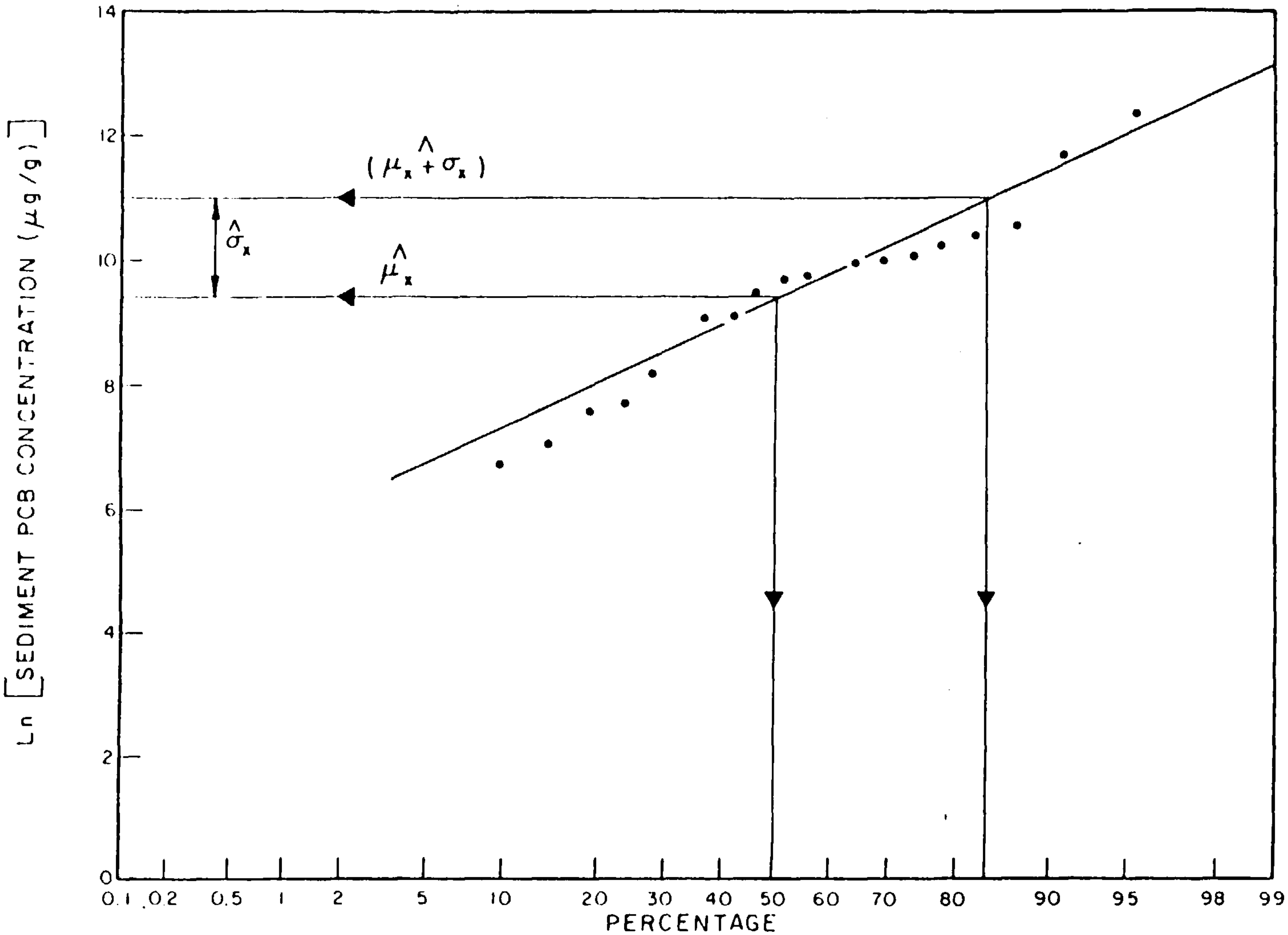


Figure 9. Frequency distribution of the Ln [sediment PCB concentration]

TABLE I

ESTIMATES OF PCB MASS IN THE SEDIMENTS OF

WAUKEGAN HARBOR AND NORTH DITCH

	Best Estimate	High Estimate	Low Estimate
Waukegan Harbor	207,100 kg (456,650 lbs)	343,300 kg (756,980 lbs)	75,640 kg (166,780 lbs)
North Ditch	277,360 kg (611,580 lbs)	527,480 kg (1,163,100 lbs)	49,810 kg (109,830 lbs)
Total	484,460 kg (1,068,230 lbs)	870,780 kg (1,920,080 lbs)	125,450 kg (276,610 lbs)

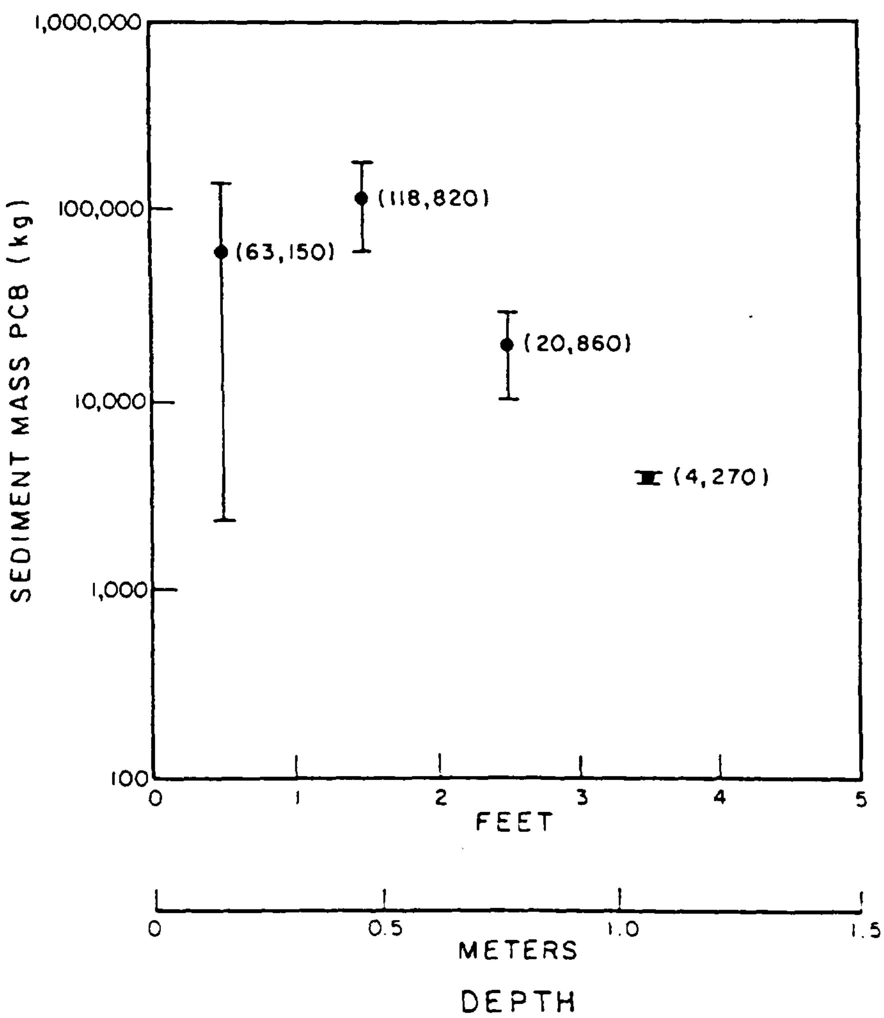


Figure 10. Estimated mass of total PCB in Waukegan Harbor sediments

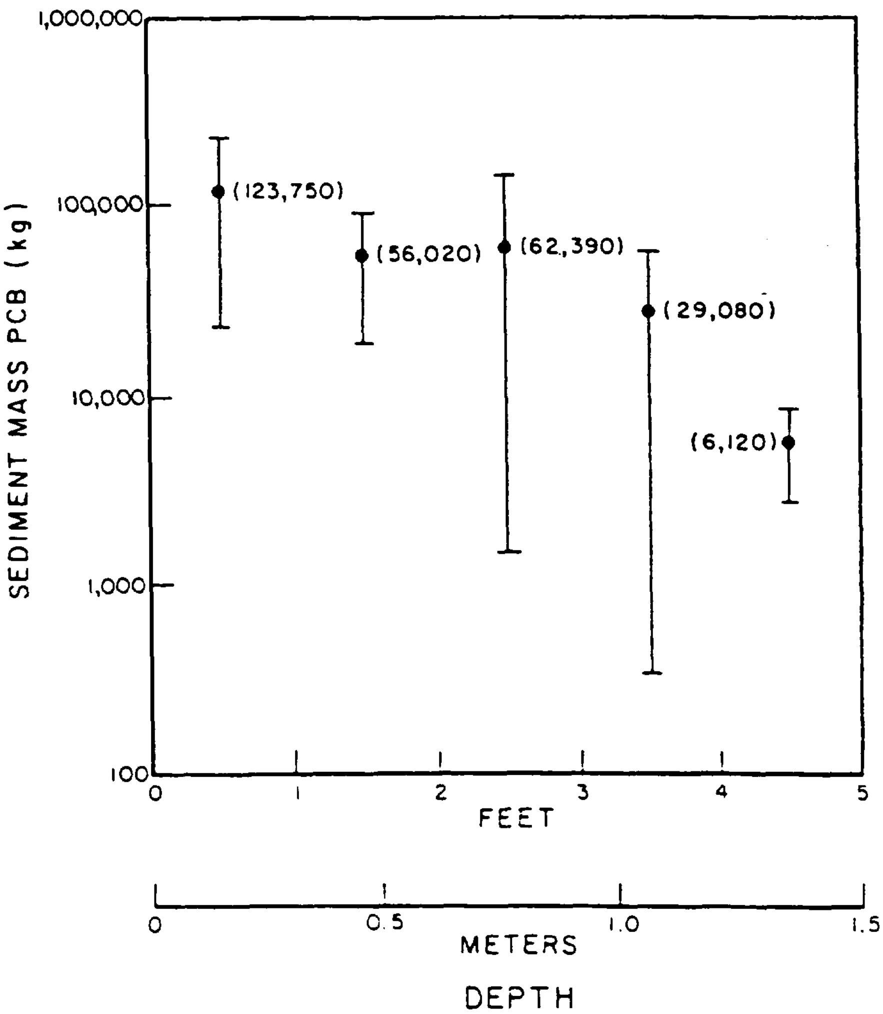


Figure 11. Estimated mass of total PCB in North Ditch sediments

In Figure 12 the PCB mass in the Waukegan Harbor and Harbor-Ditch system are shown. As indicated in Section 11 of this report, the total amount of PCB purchased over the period 1955-1970 is estimated at 5,300,000 kg. The "best estimate" of the mass of PCB in the Harbor-Ditch system therefore represents about 9% of the total purchased. It is not clear therefore, at this point in the analysis, whether any significant quantity of PCB escaped to Lake Michigan during usage of PCB or what the present discharge of PCB is from the Harbor-Ditch system to the Lake. Subsequent sections of this Report present an in-depth analysis of this question. It is clear however that one cannot judge on the basis of the mass of PCB in the sediment alone whether there has been or whether there is now any discharge of PCB from the system.

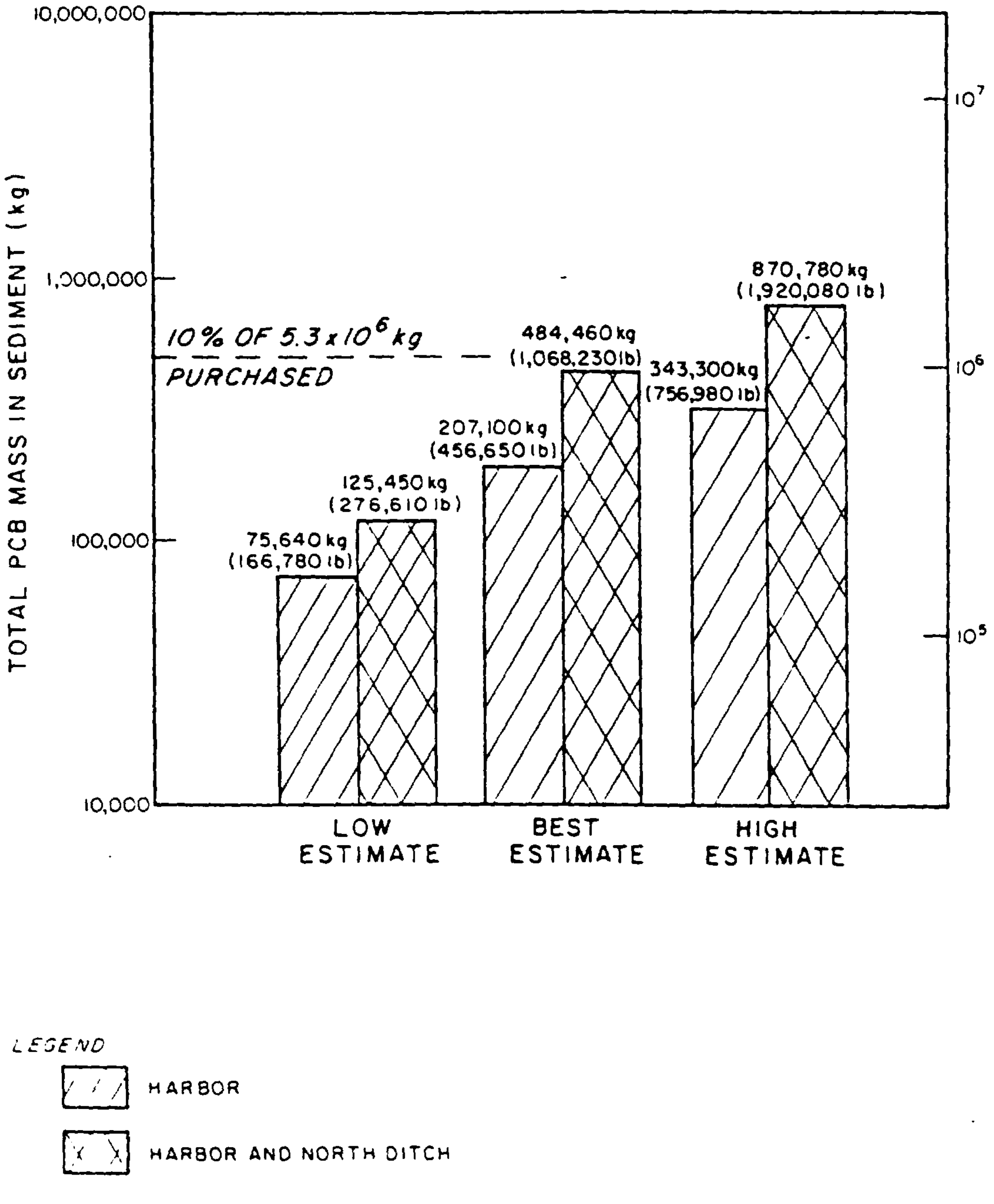


Figure 12. Estimated mass of total PCB in the Waukegan Harbor—North Ditch System

SECTION 4

DATA COLLECTION EFFORTS

A number of data collection surveys of Waukegan Harbor and adjacent areas of Lake Michigan were performed during 1979 by USEPA, Argonne National Laboratories and others. Weekly samples were taken at six Harbor stations and three nearshore Lake Michigan stations by USEPA over about a two month period. Samples were analyzed for suspended solids, total PCB and particulate PCB. Harbor surveys were also carried out by the Cranbrook Institute of Science (CIS). On two CIS surveys, May 15-17 and June 26-28, surface sediment and suspended solids were fractionated into four size classes. The PCB associated with each size class (as well as Total PCB and dissolved PCB) were measured. Argonne conducted daily surveys sampling six Harbor stations, surface and bottom, for 18 days. Temperature, chlorides, lead, suspended solids and total PCB (surface only) were measured. Argonne also conducted an instantaneous release dye study in early June. This data, along with historical data were analyzed and incorporated in the analysis. Some of these analyses are reviewed below. Sediment data, as noted previously were also collected by ERG and the University of Wisconsin.

Recent data on the North Ditch have been compiled by Mason and Hanger (1981) and sampling of PCB and suspended sediment concentrations were also obtained by the USEPA.

SECTION 5

WATER QUALITY DATA ANALYSIS

Harbor

Figure 13 presents a time history of water column (surface) total PCB measured at several stations during the daily surveys. Large day to day variations exist. However, it is apparent that the concentrations in the inner parts of the Harbor (H5 and H7) are much higher, in general, than those observed at the entrance to the Harbor (H14). It should be noted that the sharp decrease in concentrations evident around May 9-10 are believed to be the result of the flushing out of the Harbor by "clean" Lake water. Similar behavior is pointed out later for chlorides data collected during this period.

The daily data were analyzed statistically. Figure 14 shows the concentration of Total PCB along a centerline transect through the Harbor, while Figure 15 presents probability plots of this data. In both figures it can be seen that the difference between the inner Harbor and the mouth of the Harbor is approximately one order of magnitude. The data at each station approximates a logarithmic distribution and the standard deviation at each station is the same in terms of order of magnitude.

As with the analysis of the sediment PCB data, the wide variability in the data makes precise definition of water column concentrations difficult. This can have significance when attempting to estimate the quantity of PCB which is presently being discharged from the Harbor to Lake Michigan.

Figure 16 shows the Total PCB associated with the suspended solids on a dry weight basis. A difference of over three orders of magnitude exists between the highest concentrations observed on the solids in the inner Harbor and the lowest measured in near-shore Lake Michigan. In the inner Harbor almost a two order of magnitude difference exists at each sampling location.

Similarly, for the surface sediments the difference in observed concentration between the Harbor and the Lake is over five orders of magnitude with several orders of magnitude variation evident at individual locations. This is shown in Figure 17, which is the same as Figure 4.

Figure 18 presents the Total and Particulate PCB measured during one of the two "fractionation" surveys conducted by CIS.

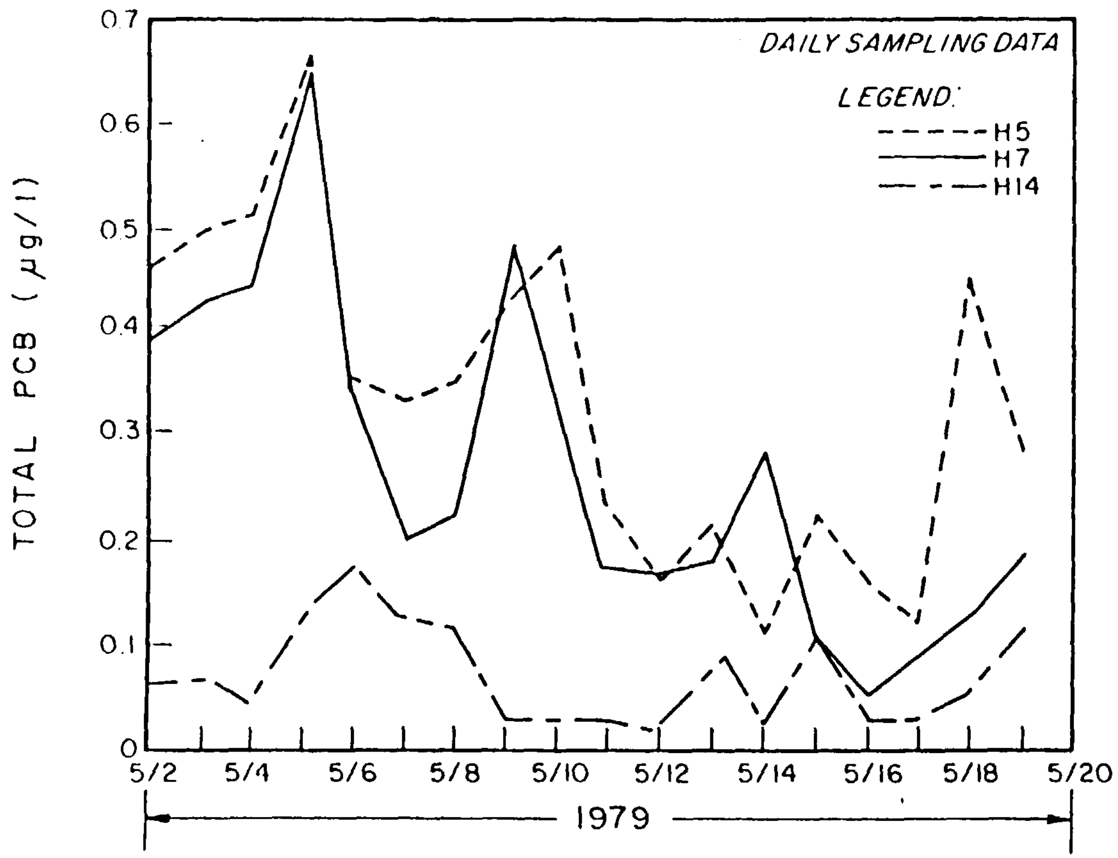


Figure 13. Daily variation in
water column total PCB concentrations at selected harbor stations

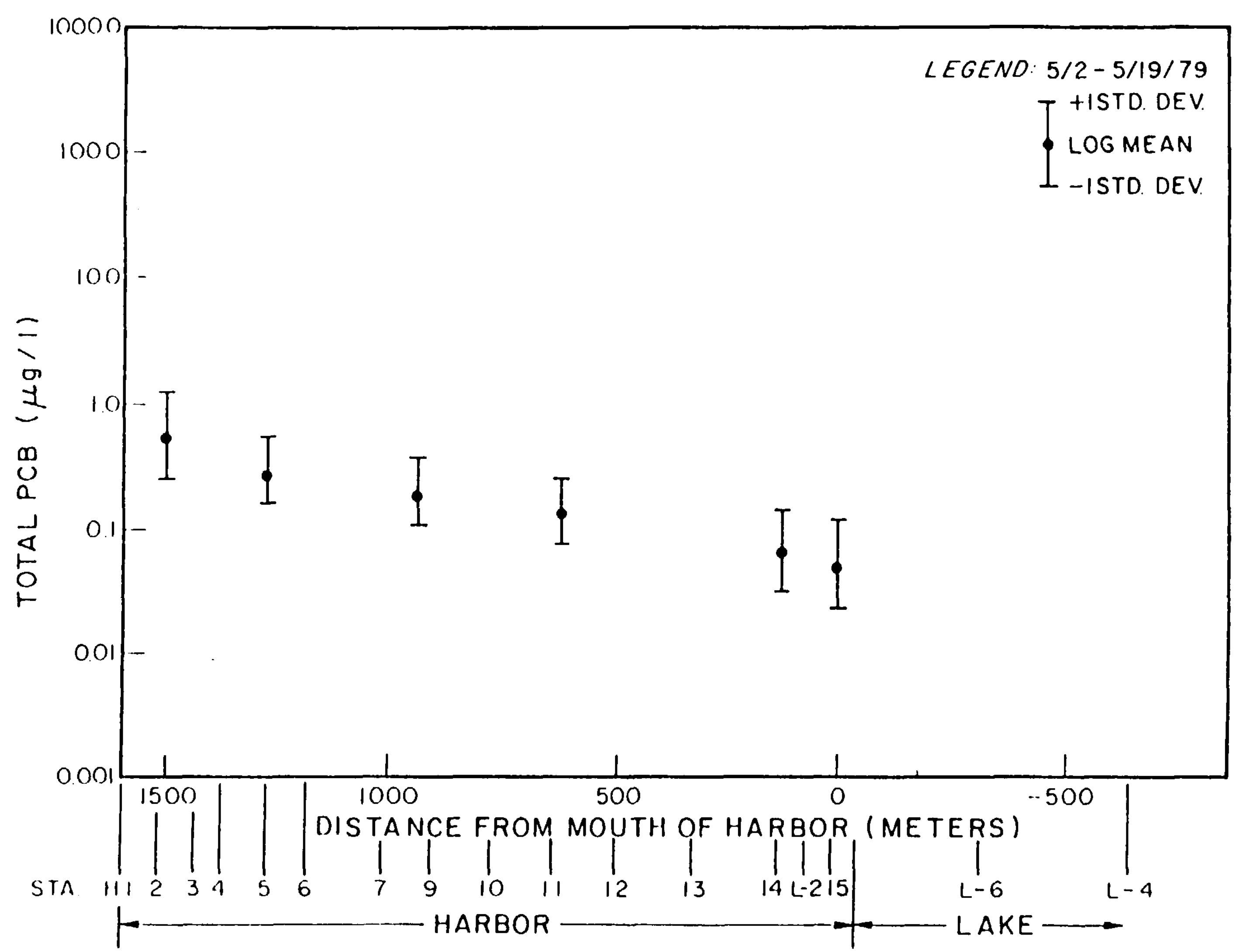


Figure 14. Water column total PCB during the daily survey period

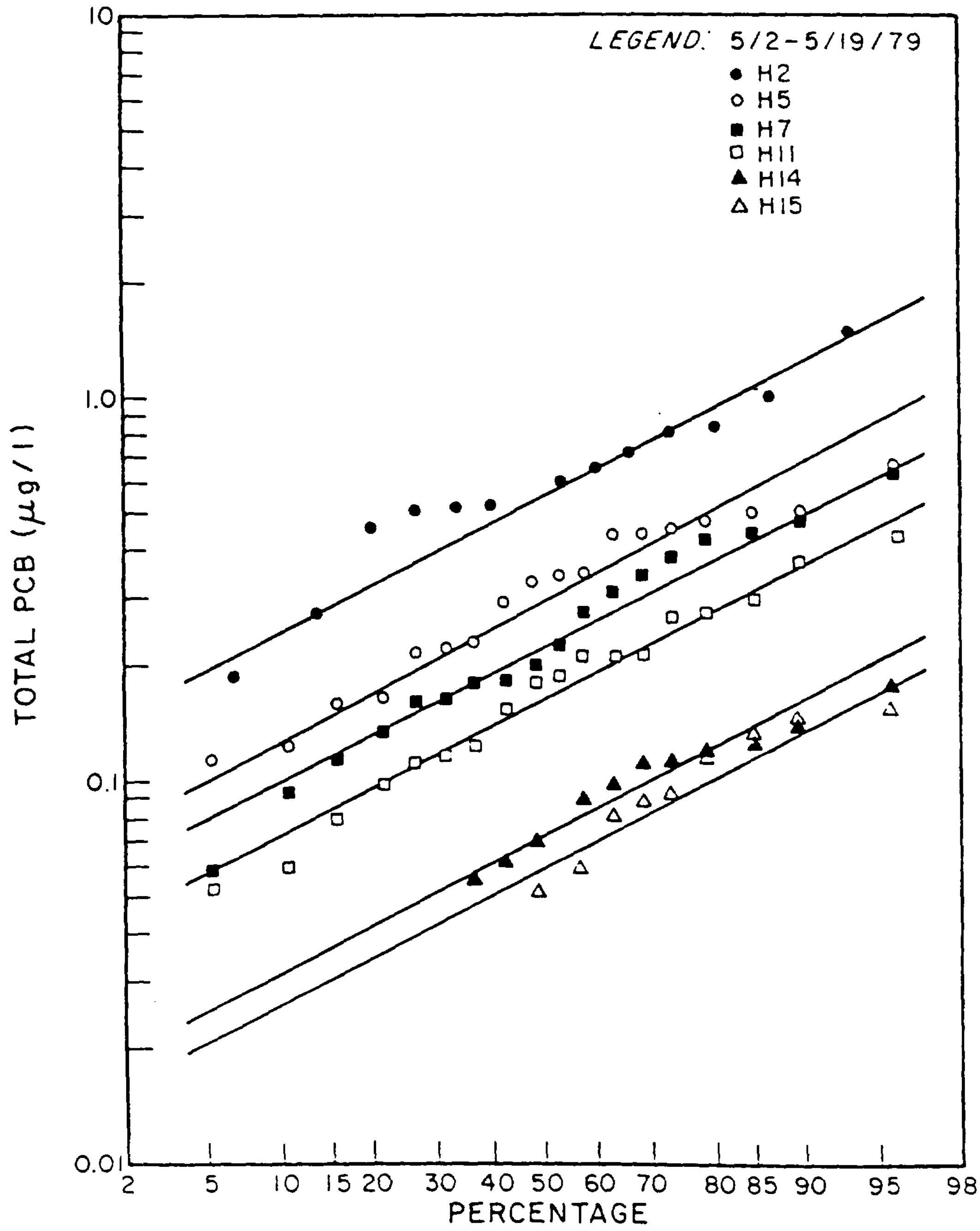


Figure 15. Frequency distribution of harbor water column total PCB concentrations

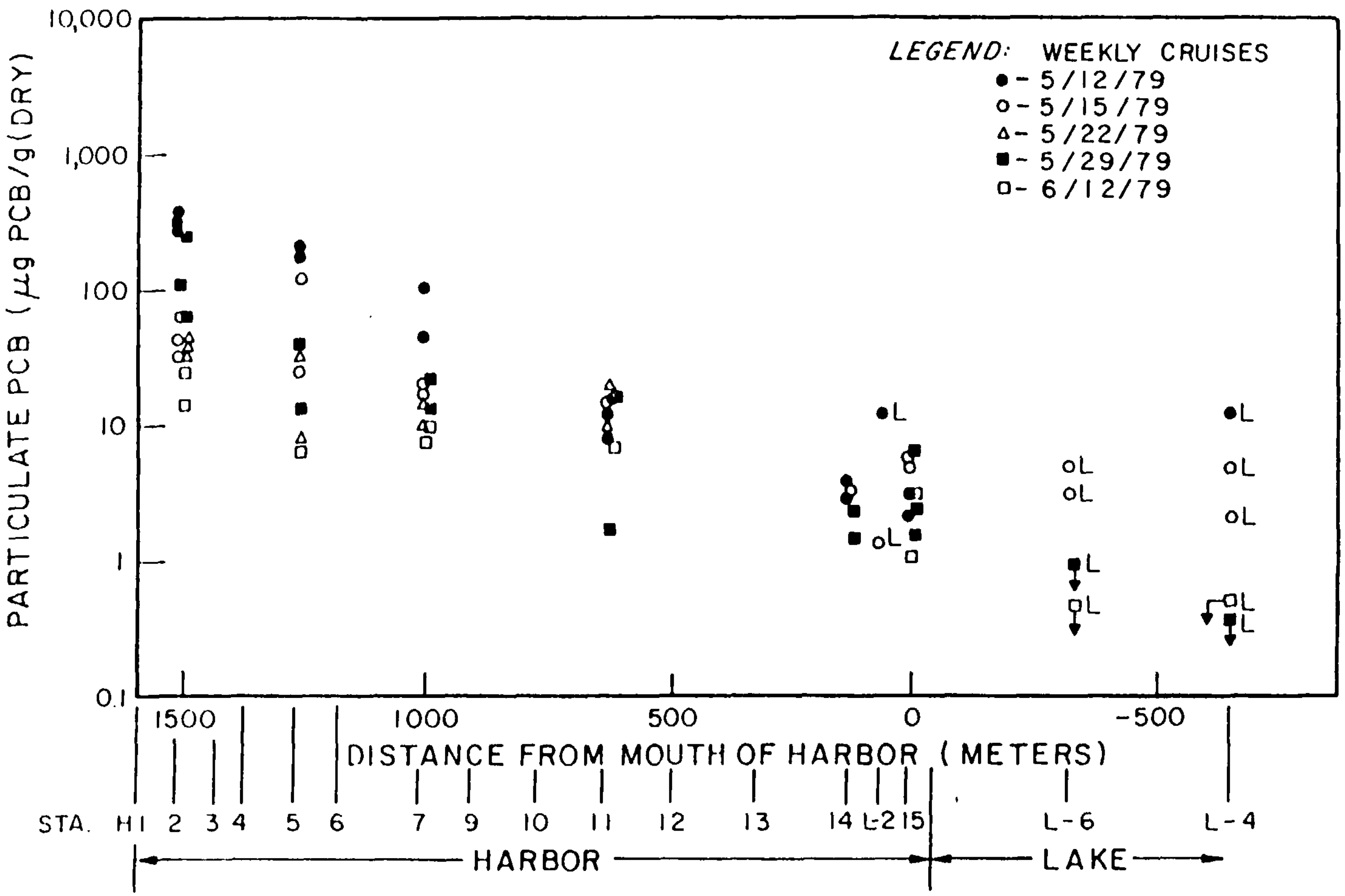


Figure 16. Water column particulate PCB data

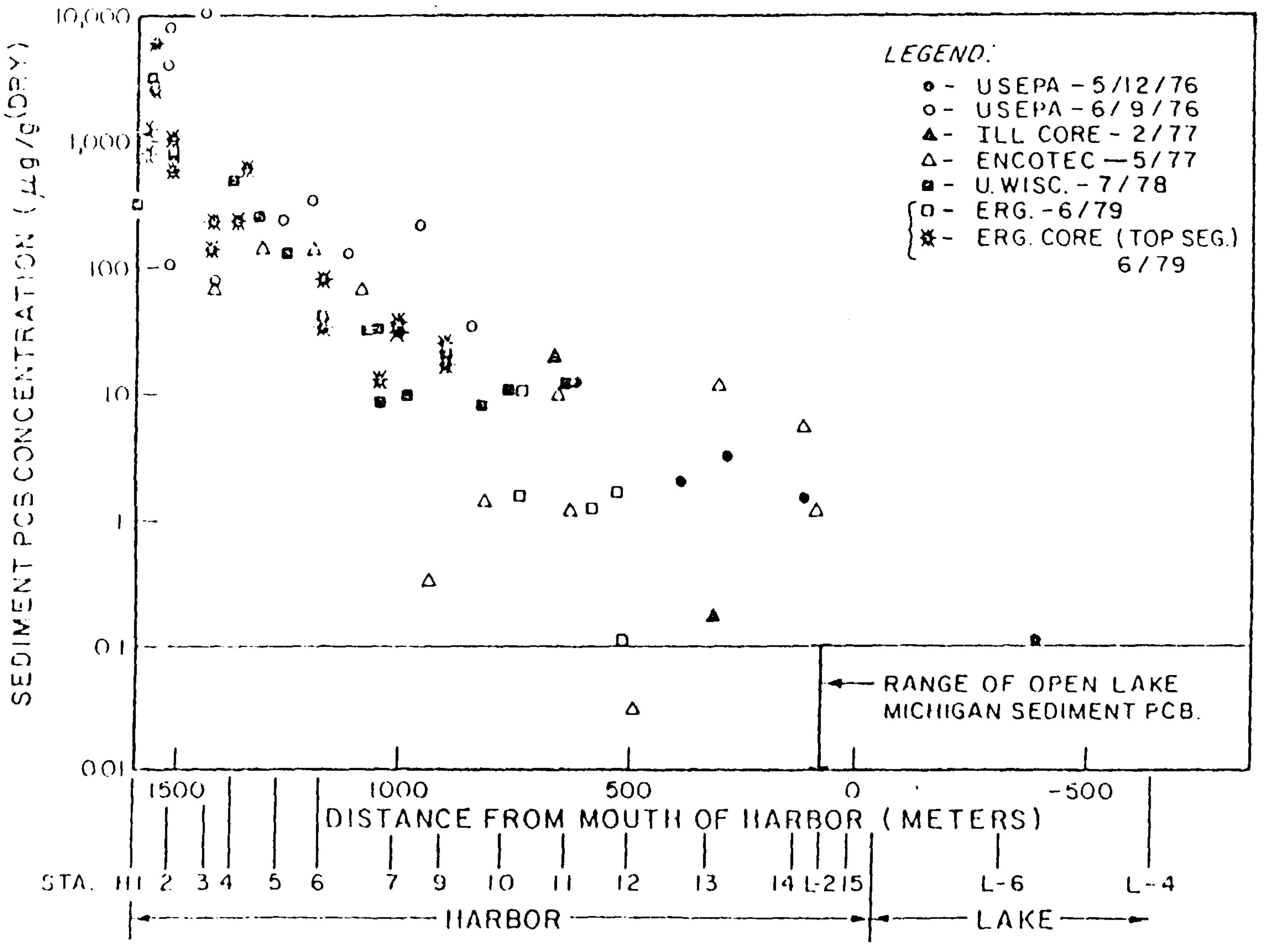


Figure 17. Surface sediment total PCB concentrations

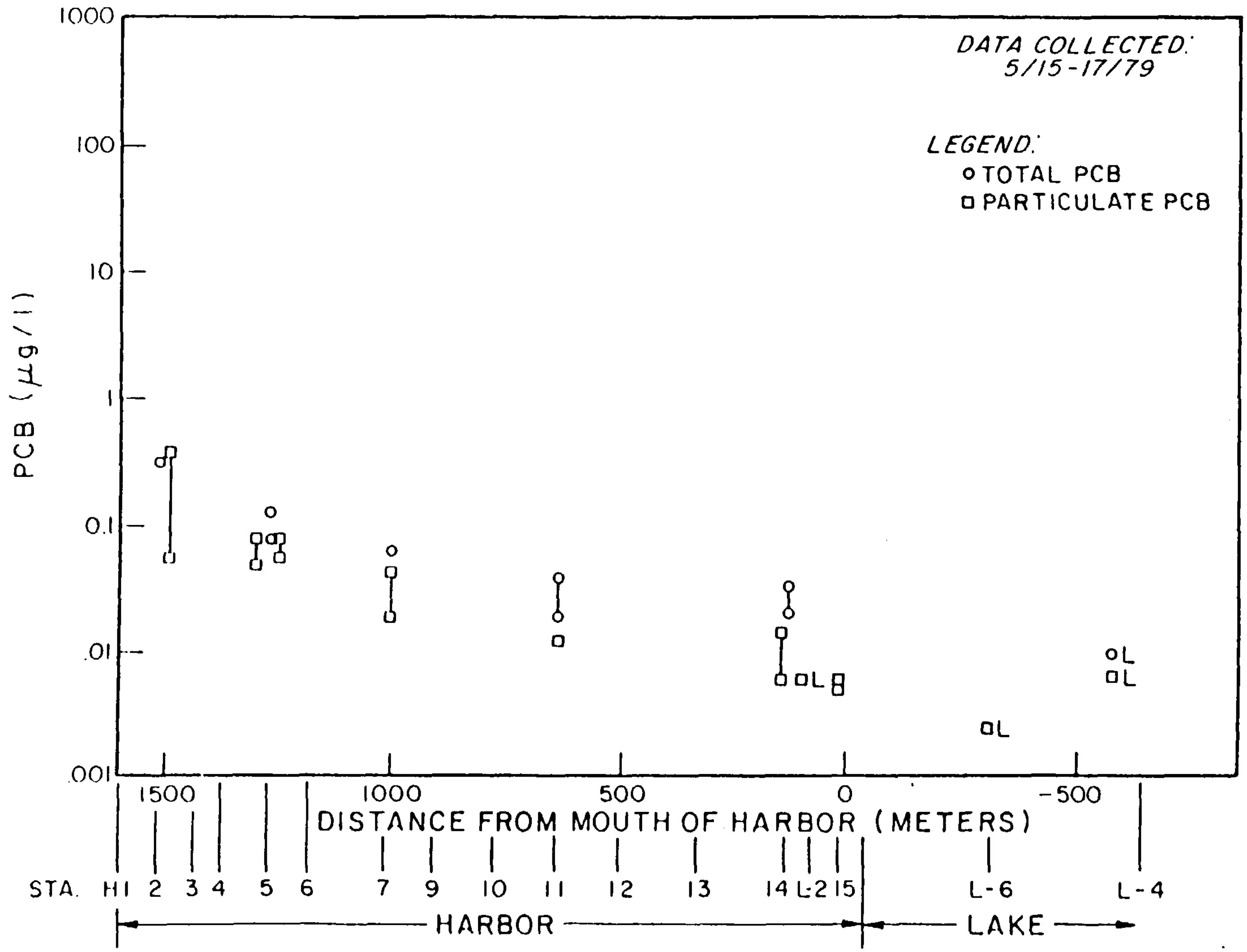


Figure 18. Total and total particulate PCB concentrations

Both Total and Particulate PCB decrease in concentration as the distance from the mouth of the Harbor decreases. The rate of decrease appears to be about the same for both the Total and the Particulate PCB.

As mentioned above, a series of samples were fractionated and analyzed for suspended solids and total PCB. The five size classes measured were:

Size 1	$C_{p1} > 74\mu$
Size 2	$74\mu > C_{P2} > 37\mu$
Size 3	$37\mu > C_{P3} > 10\mu$
Size 4	$10 > C_{P4} > 0.7\mu$
Size 5	$0.7\mu > C_{P5}$

Anything less than 0.7μ was considered dissolved.

The Suspended Solids in two particle size classes (Size 2 and 4) are shown in Figures 19, 20, and 21. The distribution of suspended solids in each size class have similar shapes with the higher concentrations at the lower end of the Harbor and lower concentrations at the upper end of the Harbor.

The PCB associated with the solids in each size class during the survey are presented in Figures 22 and 23. In each class the highest concentrations are measured in the inner Harbor and the lowest are observed in at the mouth of the Harbor. As with the suspended solids data, the shapes of the profiles are all similar.

The concentration of PCB on the suspended solids in two size classes are shown in Figure 24. Little or no difference is seen in the concentrations (ν) associated with either size class. Similarly, no difference is observed in the partition coefficients (a') calculated from this data for each of these size classes. One concludes from the data of Figure 24 that for the two size classes, there is no appreciable difference in the sorption of PCB, i.e., there is no tendency for the PCB to preferentially adhere to the smaller particles.

Ditch

Figure 25 gives a summary of the available data for the period between March and September 1979. The precipitation data were obtained from the climatological data for the State of Illinois 1979, Waukegan Station 4 WSW. The discharge, suspended solids and total PCB concentration are from samples collected at the Footbridge, which is located approximately 200 ft above the mouth of the Ditch.

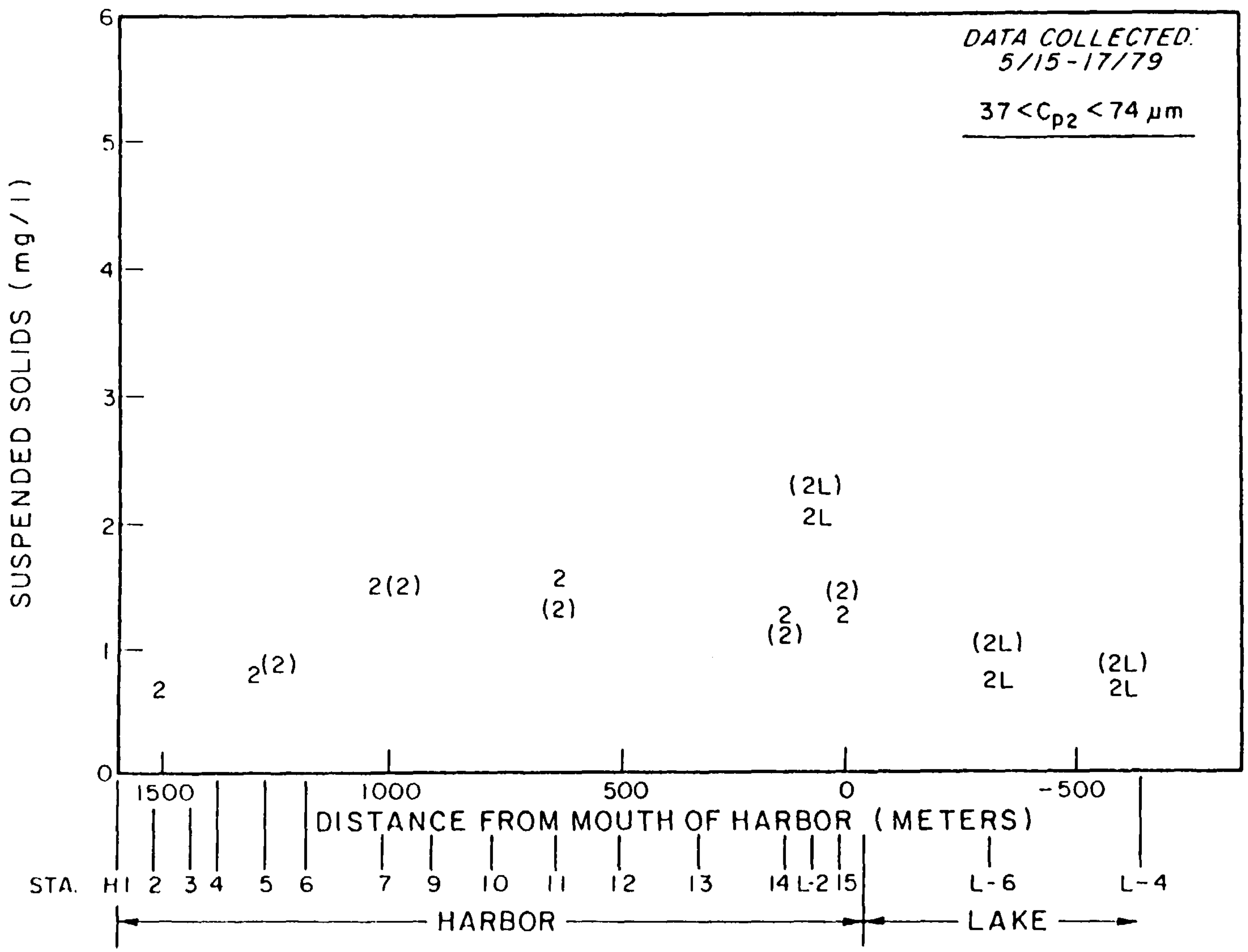


Figure 19. Suspended solids concentrations – Size class 2

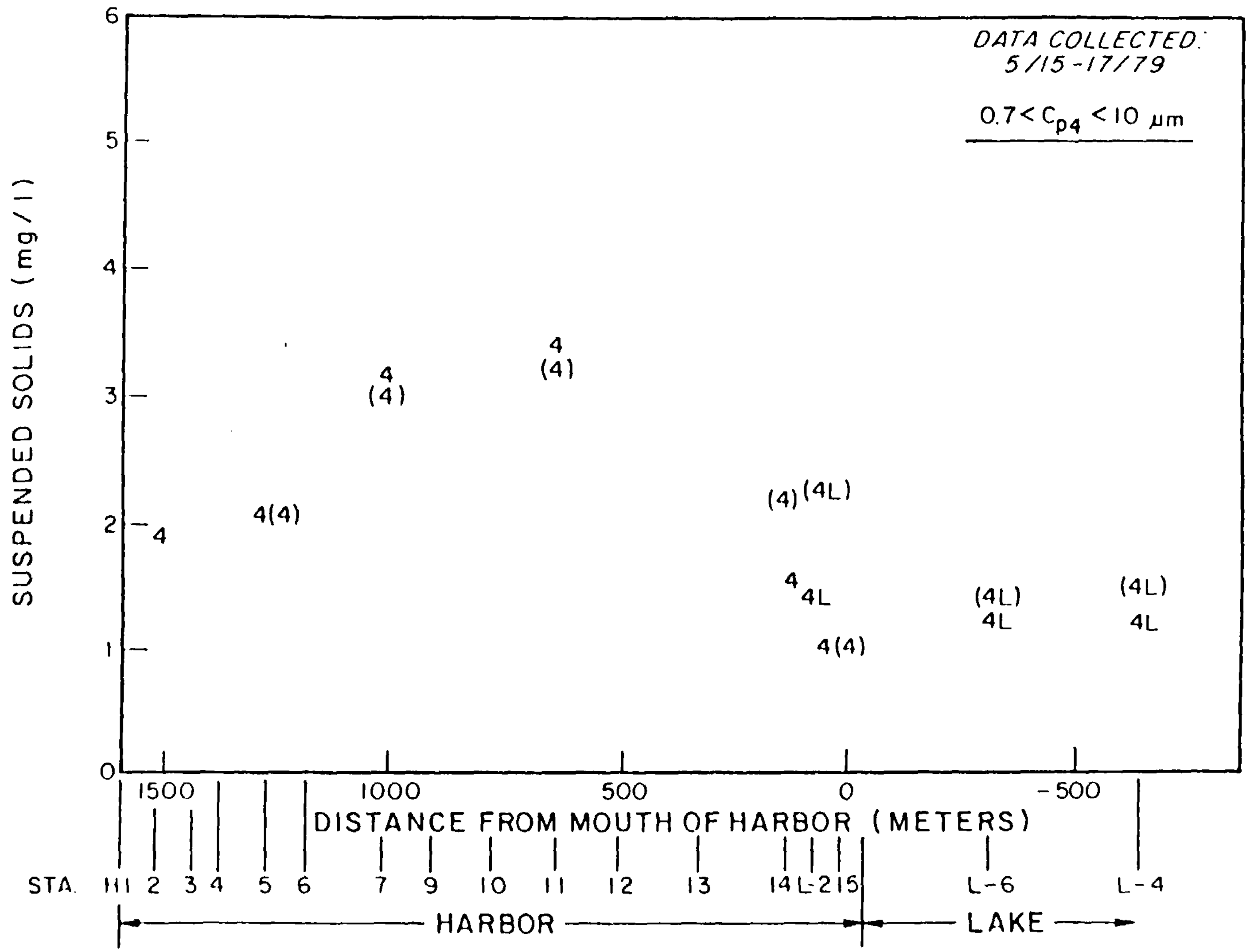


Figure 20. Suspended solids concentrations – Size class 4

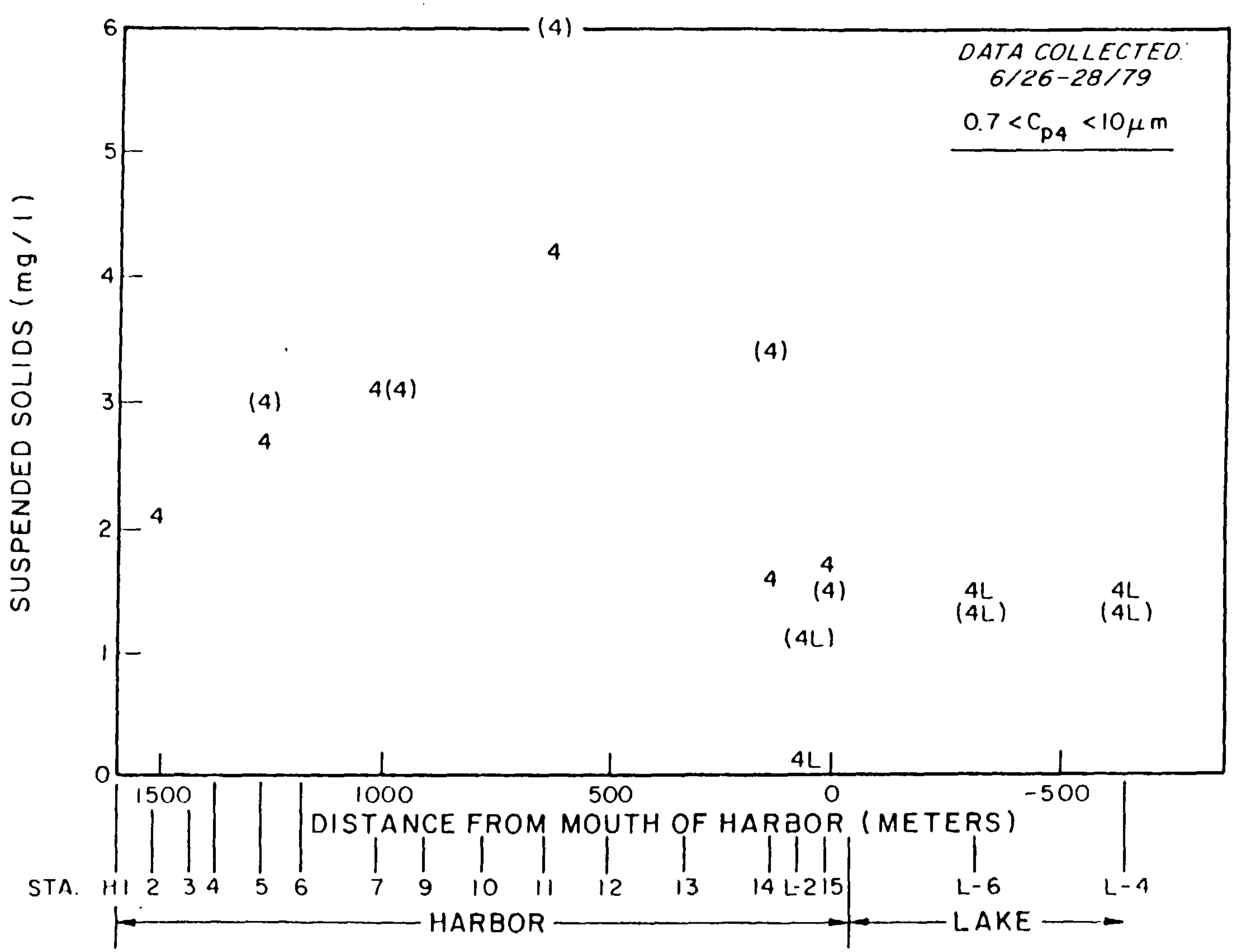


Figure 21. Suspended solids concentrations – Size class 4

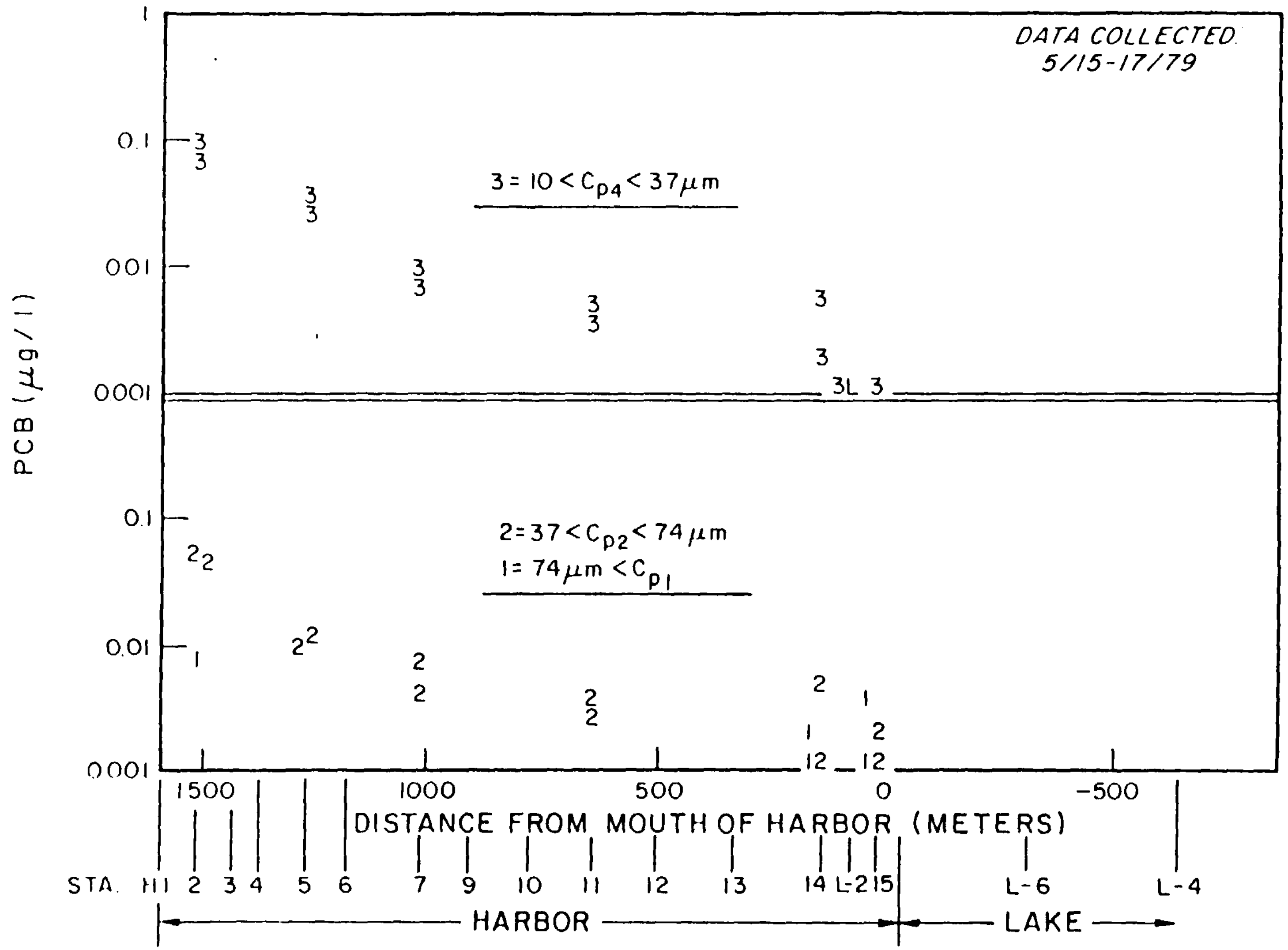


Figure 22. PCB associated with suspended solids - Size classes 1, 2, 3

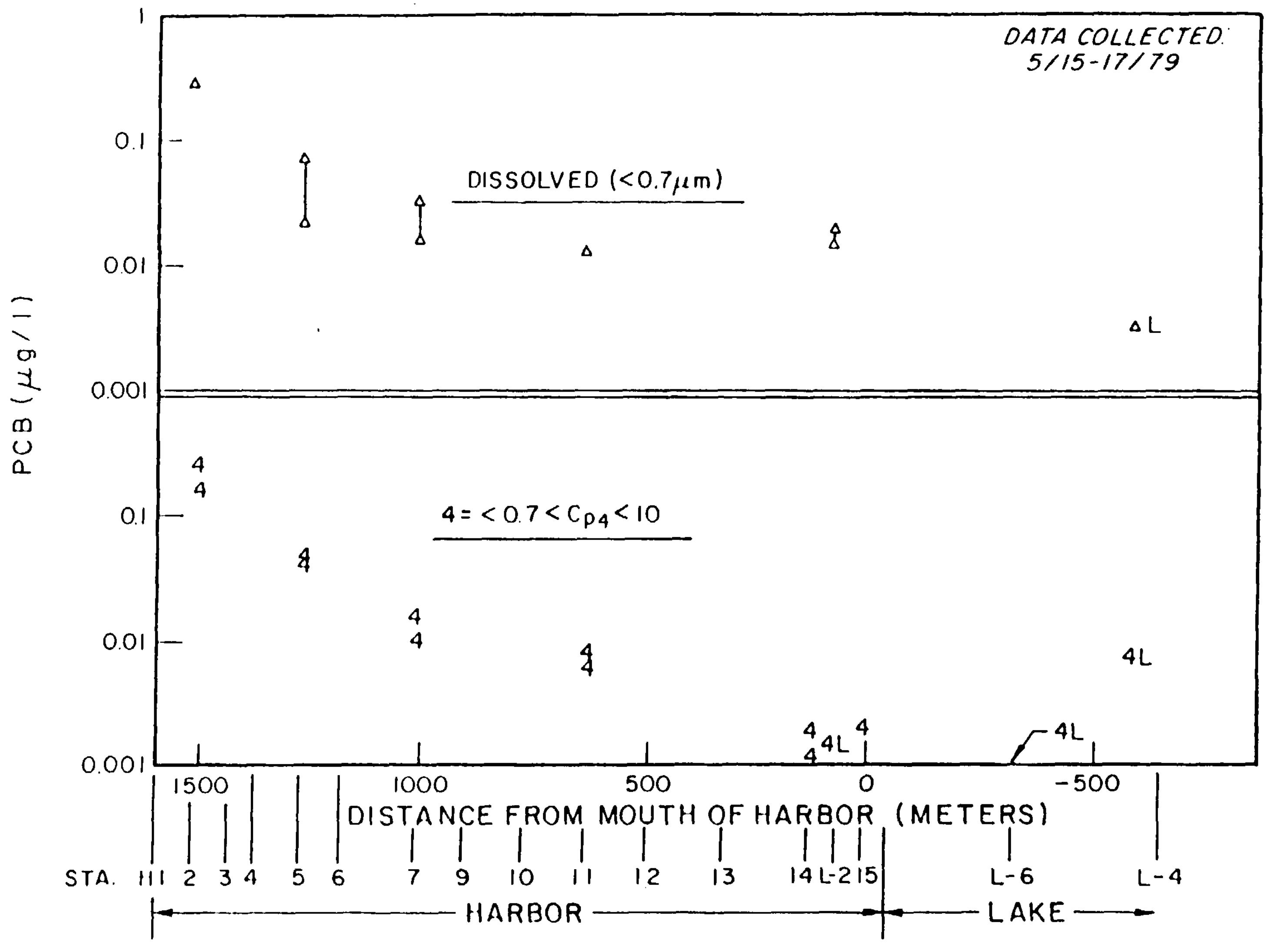


Figure 23. PCB associated with suspended solids - Size classes 4,5

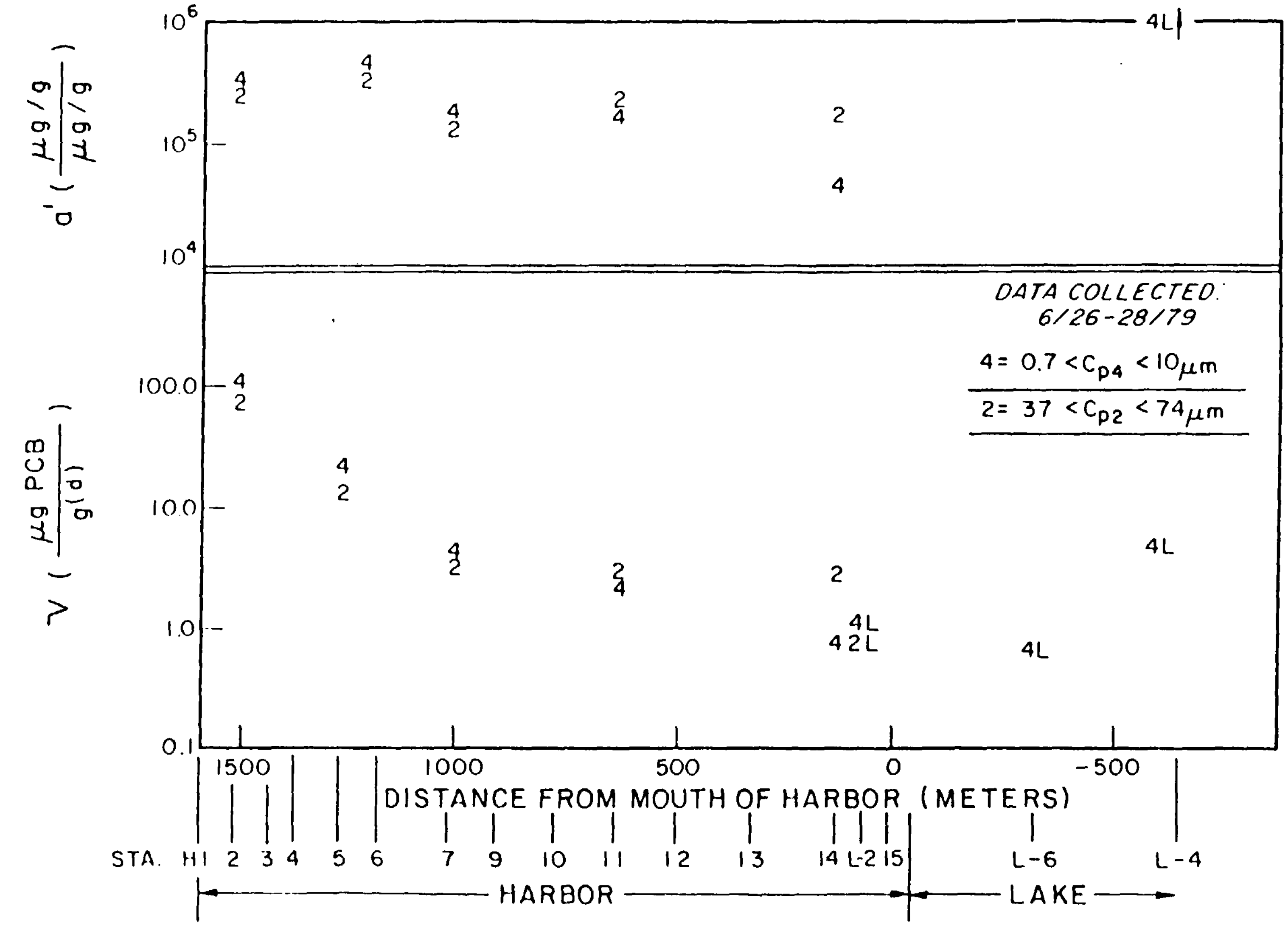


Figure 24. Partition coefficient and PCB associated with suspended solids - Size classes 2,4

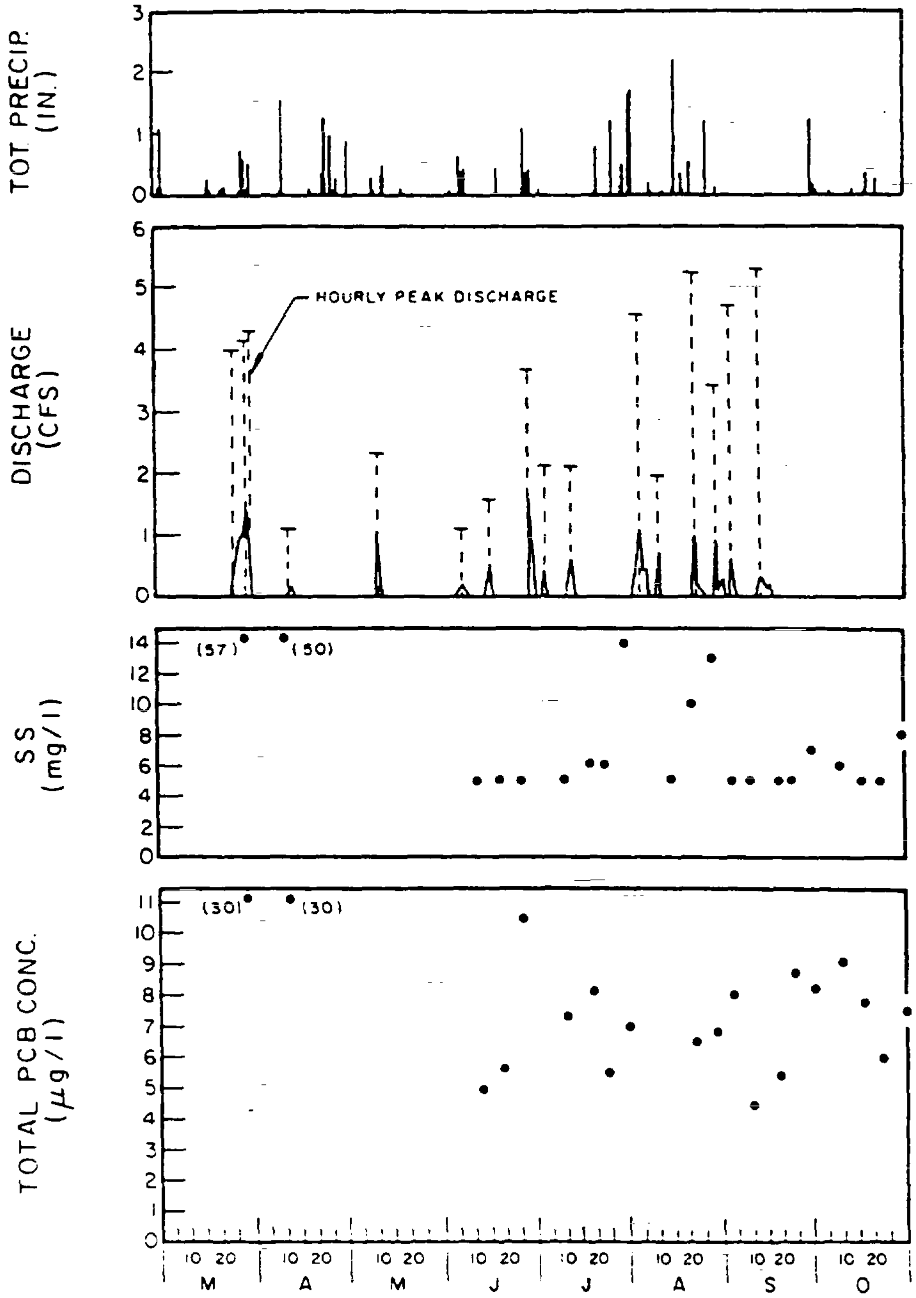


Figure 25. Data record for March to November, 1979 at gage 1 (Footbridge)

From a comparison between the rainfall record and measured discharge, it can be seen that the runoff cannot be determined from an analysis of the rainfall alone. It has also been noted (Noehre and Gray, 1980) that during some storm events there is no net discharge for the Ditch due to backwater condition at the mouth.

During rain events, the flow however was apparently estimated over a long term average period

$$Q = 26.89 \text{ CIA}$$

where

Q is the average flow (cfs), C is the runoff coefficient, I is the average rainfall (in/d) and A is the drainage area (mi^2).

During the period from June through October, there were 48 days for which there was measurable rainfall. For these occasions, there was an average of 0.38 in/d (.97 cm/d). Using the above expression and an average flow of approximately 0.46 cfs, a runoff coefficient of 0.4 can be estimated.

Excluding the March and April events, the mean of the suspended solids concentration is 6.5 mg/l and the mean of the total PCB concentration is 6.94 µg/l. From the constancy in the profile and the low value of the mean suspended solids concentration, it is reasonable to make a steady state estimate of the PCB flux.

Using the mean of the PCB data, the average flow of about 1 cfs, a flux of 0.04 lb/d (0.018kg/d) is estimated, or for the period from June through October a flux of about 1.9 lb (0.87 kg). Extrapolating over the entire year a flux of about 4.6 lb or 2 kg of PCB is estimated. The flux at the Footbridge and the flux at the mouth of the ditch are assumed to be equal due to the proximity of the Footbridge to the mouth.

Figure 26 gives a summary of the available data for the March 30, 1979 event. The flow data in the extreme upstream and downstream stations are given in terms of gage heights. The rating curve of the downstream gage was derived from the sediment discharge vs flow discharge relationship for the downstream station. In Figure 26A, the flow at the upstream station was calculated from the derived rating curve of the downstream station. Figure 26B indicates that the peak concentration of the suspended solids at the mouth, downstream station, is twice the peak of the suspended solids concentration of the upstream station, the difference can be attributed to the runoff solids and solids resuspended from the bottom of the ditch. Figure 26C

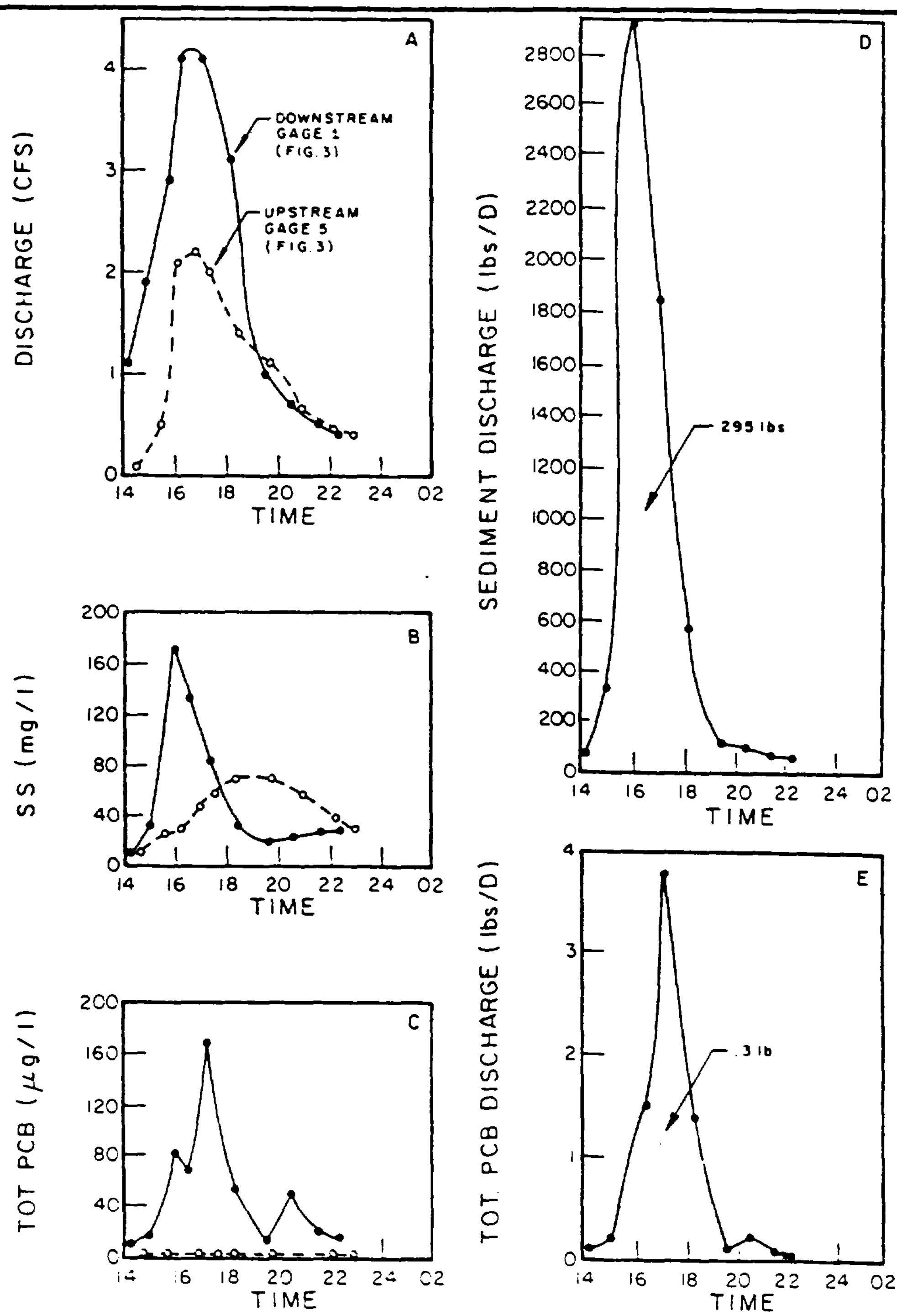


Figure 26. Summary of the March 30, 1979 Event

shows the total PCB concentration at the two extreme stations. The observed dramatic difference in the concentration is a very strong indication that any flux of PCB from the mouth to the Lake must originate from the contaminated sediments of the ditch since the flow at the upstream station is primarily stormwater. Figure 26D shows the sediment discharge rate for the event which when integrated for the duration yields the total mass of discharged sediment, which in this case is 295 lb or 134 kg. Similarly, Figure 26E gives the total PCB discharge rate which when integrated yields 0.3 lb or 0.14 kg. of PCB for the event.

SECTION 6

MATHEMATICAL MODEL OF WAUKEGAN HARBOR

A number of questions, many of which were critical to the evaluation of the impact of the PCB contamination on water quality both in the Harbor and in Lake Michigan exist. Among these are "How much PCB is being resuspended in the Harbor?" and "How much of this resuspended PCB is being discharged from the Harbor to Lake Michigan?" In order to provide quantitative estimates of the answers to these and other questions, a mathematical model was being prepared of Waukegan Harbor and the near-shore areas of Lake Michigan surrounding the Harbor.

The major interactions included in the model, other than hydrodynamic transport are adsorption-desorption of PCB to suspended matter, the settling of suspended materials, and the resuspension of sediment from the bottom sediments. A short description of these phenomena follows.

PCB's exist in a body of water in two main components, the dissolved and the particulate phases. The dissolved component includes that part of the PCB that exists in solution (assumed less than .7 μm) and the particulate component includes that part of the PCB which is adsorbed on the various forms of organic and inorganic particulate (suspended) matter. The formation of these two components results from the characteristic low solubility and high adsorbability of PCB. The particulate component is subject to settling thus contaminating the bottom sediments. On the other hand, the bottom sediment can be resuspended via the shearing action of the overlying water and through the actions of organisms that inhabit the upper layer of the bottom sediments. The existence of contaminated bottom sediment gives rise to dissolved PCB in the interstitial water, which may diffuse dispersively into the overlying water. At the air-water interface, there are exchanges of dissolved PCB between the water column and the atmosphere. These are believed to be insignificant on the scale of Waukegan Harbor, however, and were not included in the kinetic framework. It is assumed that the amount of PCB in the food chain, above the planktonic level, is small. This implies that the interaction between the abiotic and biotic sector is negligible and can be ignored when analyzing the abiotic sector. The PCB associated with the plankton is included in the particulate PCB component.

For purposes of computation, the Harbor was divided into sixteen homogeneous segments and Lake Michigan was segmented into an additional fifteen. Figure 27 shows the geographical distribution of the computational grid of the model. Vertically,

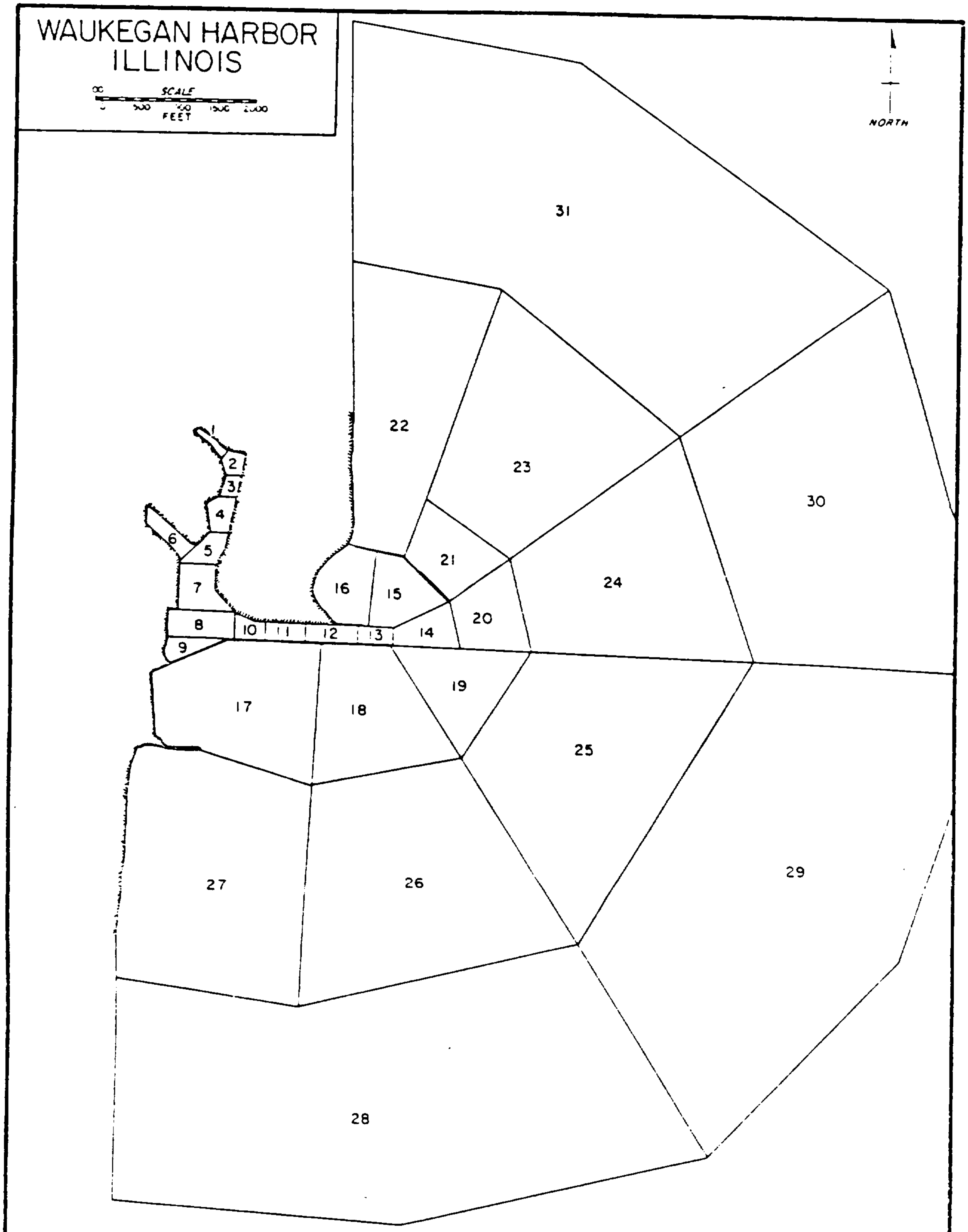


Figure 27. Segmentation of mathematical model

each segment was considered completely mixed in the water column. The sediment underlying each segment of the Harbor and Lake was incorporated with a vertically well mixed sediment segment.

The geometry (volumes, and interfacial areas) of the region was prepared from information obtained from several sources. NOAA chart 14904, "Lake Michigan, Wisconsin, Illinois, Port Washington to Waukegan" provided depth and cross section data. Additional sounding information was taken from U.S. Army Corps of Engineers Charts and soundings presented in the Argonne study (1979).

Transport between segments represented both advective and dispersive phenomena. Approximately .09 m^3/sec (3 cfs), representing the known cooling water withdrawal from the Harbor, was directly transported from the eastern boundary of the model into the Harbor. This water was then withdrawn from the inner Harbor and discharged back into Lake Michigan and routed out the southern boundary of the model. No other significant continuous inputs or withdrawals of water were included or are known to exist.

The horizontal dispersive transport coefficients used in the model were obtained using observed chloride and dye concentrations in the water column. Information on the analysis of these data is presented below.

Total suspended solids and total PCB were also modeled. Because the adsorption-desorption processes are rapid, relative to other reactions and the time scale of the transport phenomena, it is possible to make a "local equilibrium" assumption, i.e. the two phases of PCB, dissolved and particulate, come to chemical equilibrium almost instantaneously when compared to other phenomena. Consequently, given the total PCB and suspended solids concentrations, it is possible using a partition coefficient, a, to calculate the dissolved and particulate PCB concentration.

Thus, $$C_D = C_T \left(\frac{1}{1 + am}\right) \text{ and } \quad (1)$$

$$C_P = C_T - C_D \quad (2)$$

where: C_T = Total PCB (μg/l)

C_D = Dissolved PCB (μg/l)

C_p = Particulate PCB ($\mu g/l$)

m = Suspended Solids (g/l)

a = Partition coefficient (μg PCB/g SS per μg PCB/l)

The kinetic structure of this model is the same as the one used to describe the spatial distribution of PCB in the Hudson River (Hydroscience, 1978). In the case of Hudson River, the field data indicated a range of 50-500 $\mu g/g$ per $\mu g/l$ for the partition coefficient.

Model Calibration

For a mathematical model to be a useful tool, it must simulate, with some degree of accuracy, the complex series of physical, chemical and biological interactions which characterize the system. To ensure this accuracy with regard to the physical transport of materials, a calibration of the transport regime of the system is undertaken. This can best be accomplished using a conservative substance, i.e., a material which undergoes little or no reaction, as a tracer. Gradients of such substances, since they are unaffected by reactions, permit the refinement of the advective and dispersive transport characteristics of the system.

Calibration of the hydrodynamic transport portion of the model was accomplished using several sets of chloride data.

A relatively large gradient in chloride concentration exists between the inner Harbor and Lake Michigan. At times, the concentrations observed in the inner Harbor are almost double that measured in the Lake. The source of these chlorides is not known, although road deicing may be responsible for the very high values periodically observed as in February 1977 (Figure 28).

Two sets of chloride data, both collected during the ENCOTEC surveys in 1977, were used initially to select coefficients. Since the source of the chlorides is unknown, an arbitrary selection of loads to the inner Harbor and of Lake Michigan boundary concentrations were made. These, along with the dispersive transport coefficients, were then adjusted until the results calculated by the model reasonably simulated the observed data.

The results of this steady-state calibration are shown in Figure 28. In both the February and the April 1977 calibrations, the transport regimes are identical, only the loadings have been changed.

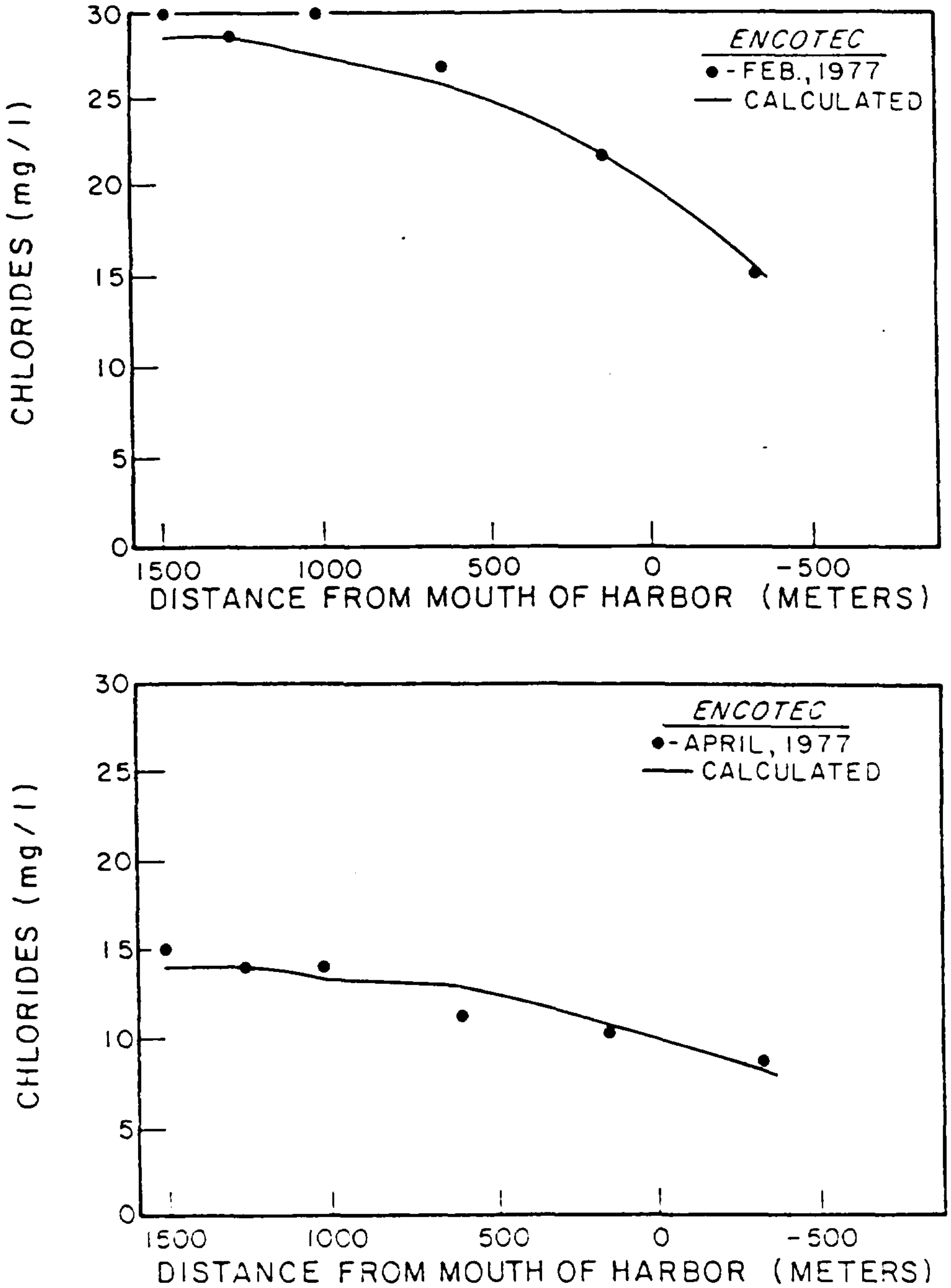


Figure 28. Comparison of observed and calculated chloride data

Advective transport was included and represented the only known source or sink of water in the harbor, less than 0.1 m^3/sec of cooling water withdrawal by OMC. Sensitivity analyses indicate that the model is insensitive to the absolute magnitude of this number at the levels believed to exist in the Harbor.

A third set of chloride data was also evaluated. These data, collected during a portion of the daily survey period, are shown along with the gradient calculated by the model in Figure 29. Again, only the loadings were changed; the exchange coefficients are identical to those obtained in the preliminary calibration. Agreement between the observed and calculated profiles is good.

Only the data collected during the period from May 2nd to May 9th was included in this latter calibration. As shown in Figure 30, two relatively steady state periods exist during the period from May 2nd to May 19th. The first exists through May 8-9 and is characterized by relatively high chloride concentrations in the inner Harbor. The second, starting on May 12th exhibits much lower concentrations in the inner Harbor. These two steady-state periods are separated by a transition period of three to four days. While a time variable simulation of this occurrence could have been performed, little useful information would have been gained since, among other things, the exact nature of the source of chlorides is unknown. As indicated earlier, the relatively abrupt decrease in concentrations of chlorides and PCB is believed to be caused by the flushing out of the Harbor by Lake Michigan water containing a low level of these constituents.

Because of the arbitrary nature of the loadings used in the chloride calibrations, a further effort was made to evaluate the validity of the transport regime selected. A dye release study was conducted by Argonne in early June 1979. A known mass of dye was released in the inner Harbor. The model, using the transport coefficients obtained during the chloride calibrations, was run in the time variable mode. The results of the simulation, in which 238 g of dye was released at the end of the day on June 4th, are shown in Figure 31. The agreement between the observed dye concentrations and those calculated by the model over the course of one week is very good.

On the basis of the three chloride calibrations and of the simulation of the dye release, the transport regime of the model appears to simulate the prototype quite well. Figure 32 presents graphically the horizontal exchange along the centerline of the Harbor arrived at by the calibration.

Once the transort phenomena were calibrated using the chlorides and dye study data, calibration procedures were undertaken for the kinetic portion of the model. Total suspended

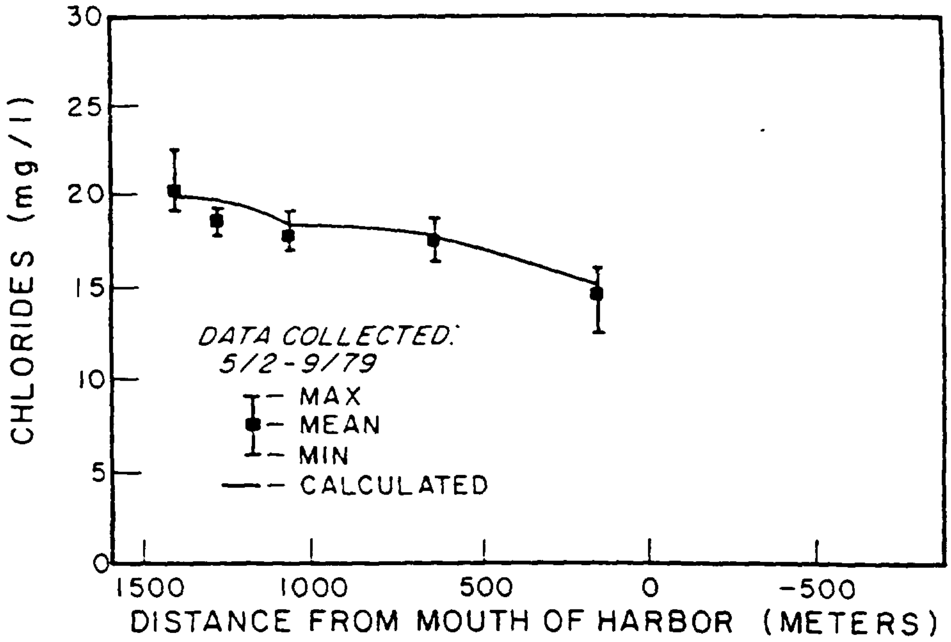


Figure 29. Comparison of observed and calculated chlorides

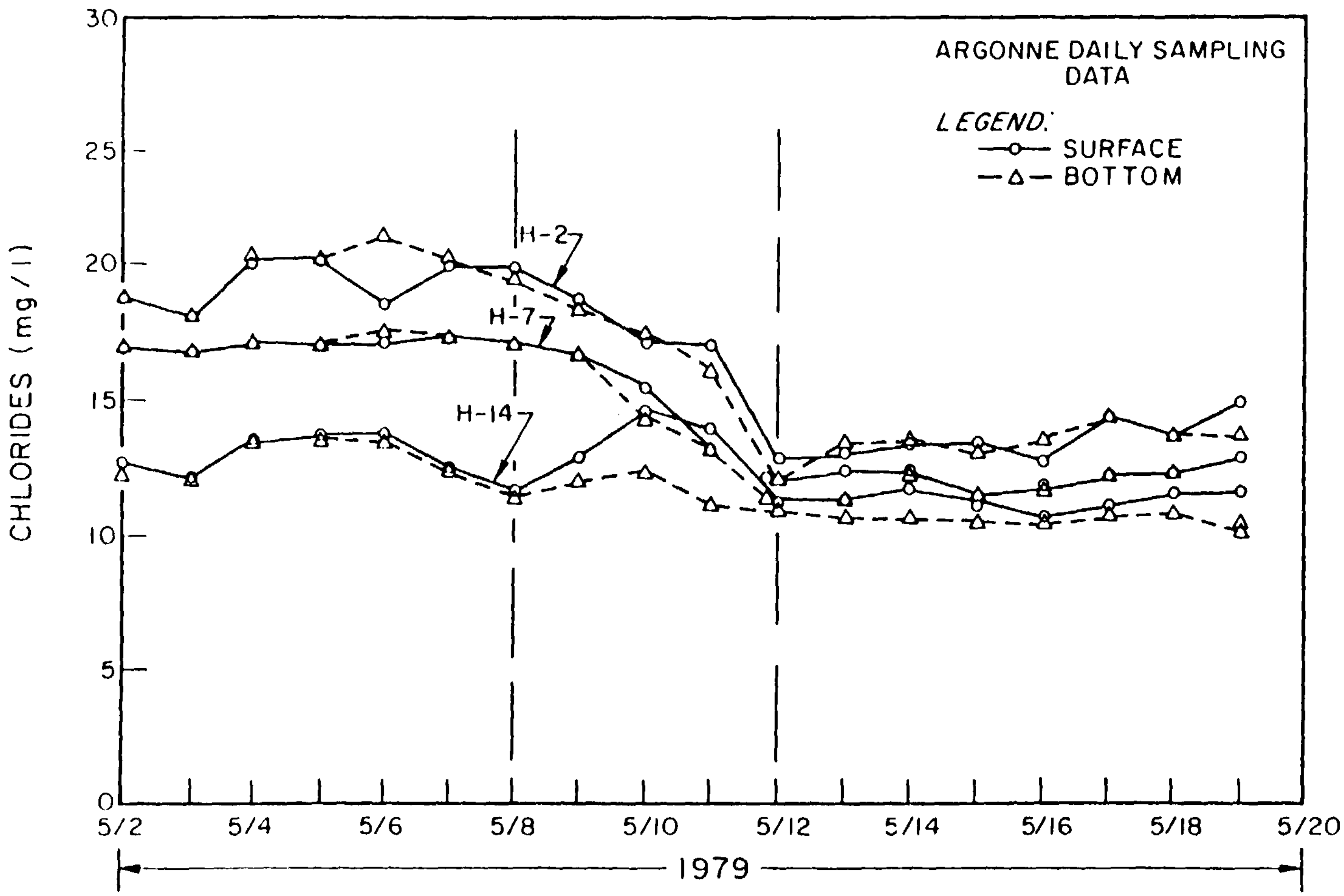


Figure 30. Observed chloride concentrations at selected stations

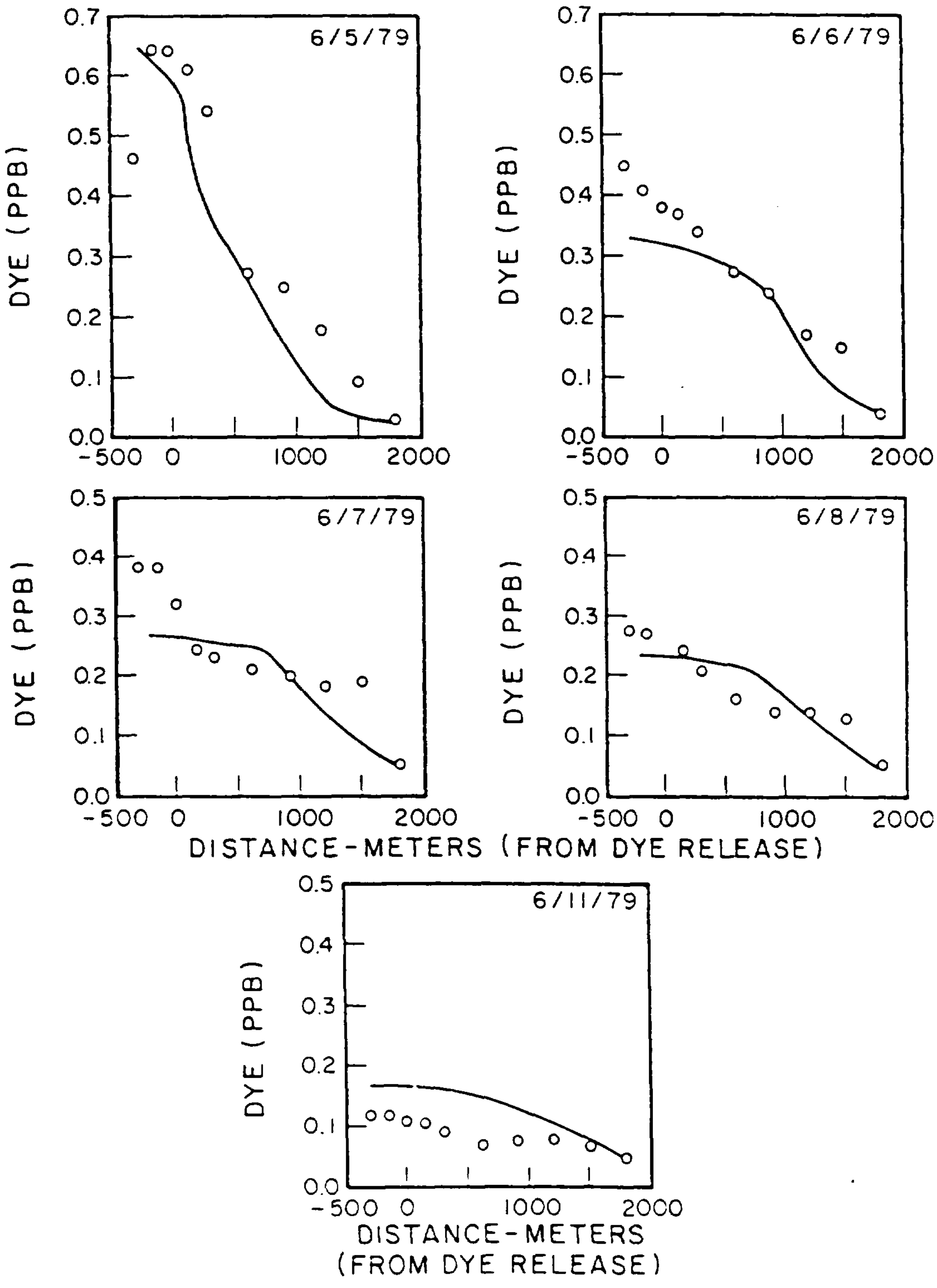


Figure 31. Comparison of observed and calculated dye concentration

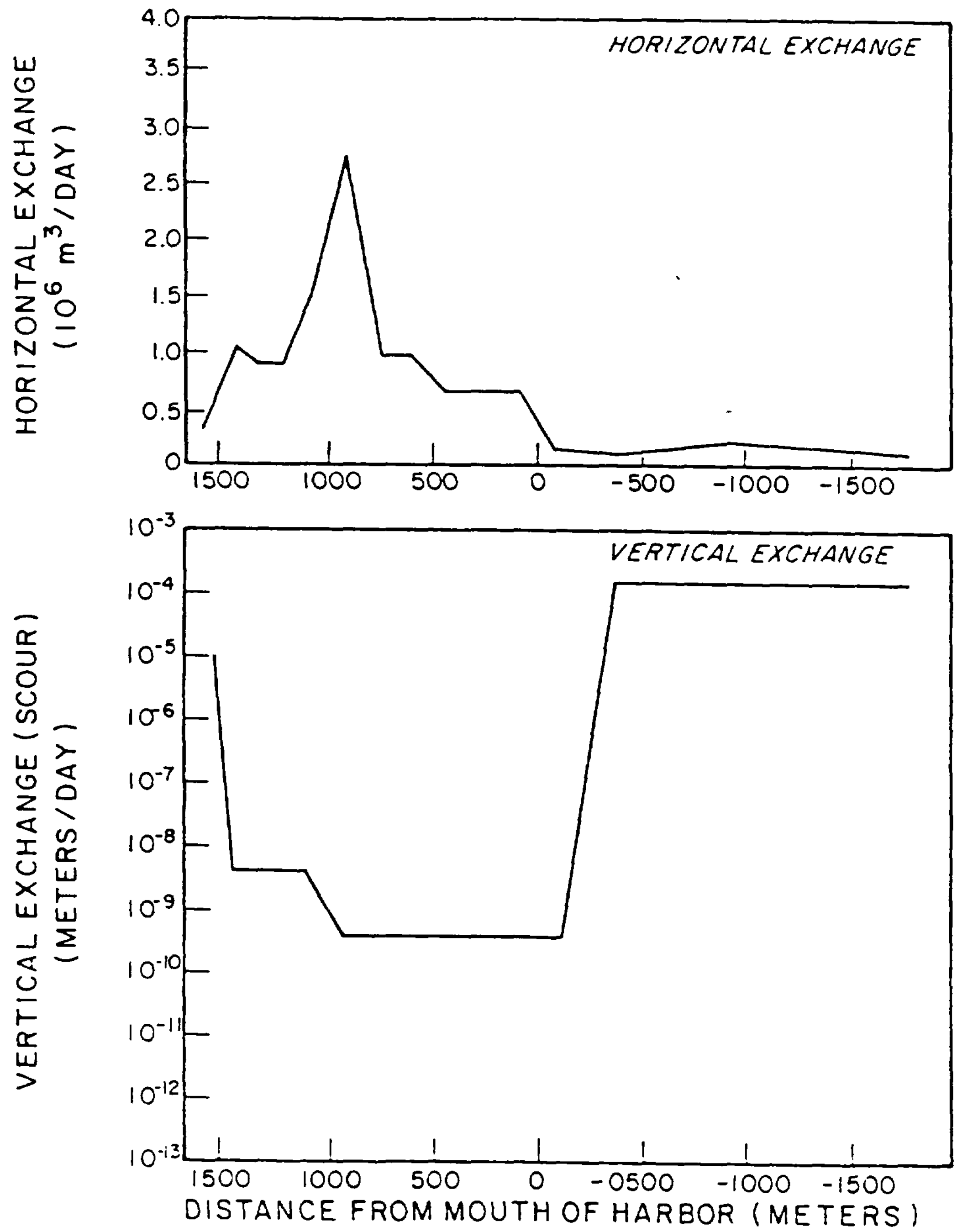


Figure 32. Horizontal and vertical exchange

solids collected during the daily surveys were used to define the settling/resuspension phenomena. Figure 33 shows the total supsended solids calibration. The calculated line reproduces the shape of the observed profile and is generally within one mg/l of the mean of the observed data and is well within one standard deviation of the data at each station.

The calibration procedures of the kinetic framework were completed using the available water column and sediment PCB data. Figure 34 presents a comparison of the calculated concentrations and that data collected during the daily surveys. Agreement is good both with regard to shape and magnitude of the profiles.

As shown in Figure 35, the particulate PCB data collected during the weekly cruises also compare favorably with the calculated line except at station H11 where the calculated value is slightly higher than the observed data. Figure 36 compares the calculated profile with sediment PCB data collected over a three year period. Agreement between the calculated and the observed is good.

Because a limited number of particulate and dissolved PCB measurements were available and because of the wide range and uncertainity associated with this small data set, a comparison of calculated and observed dissolved PCB concentrations was also made on a percent of total PCB basis rather than on an absolute concentration basis alone. This comparison is shown in Figure 37. A similar comparison is made for particulate PCB in Figure 38. In the inner Harbor more of the PCB is in the dissolved phase than associated with the suspended solids. Near the mouth of the Harbor, the converse is true. This reversal in predominance is caused by the difference in suspended solids concentrations between the two regions. Near the mouth of the Harbor, the suspended solids concentrations are higher. Consequently, there are more solids for the PCB to be associated with under equilibrium conditions. This reversal is reflected in the model results.

Figure 32 presents the horizontal and vertical transport characteristics used in the calibration. In all of these comparisons, it should be noted that the depth of the well mixed sediment available for resuspension, the resuspension velocity, and the vertical settling velocity are all parameters that are subject to wide variability. The choice of the parameters shown in Table II represented the best set of parameters, but not necessarily the unique set, that reproduces the data. Other combinations of parameters could provide similar agreement. For example, the selection of the sediment bed depth of 20 cm was somewhat arbitrary because comprehensive core data were not available for an adequate description of the total PCB depth

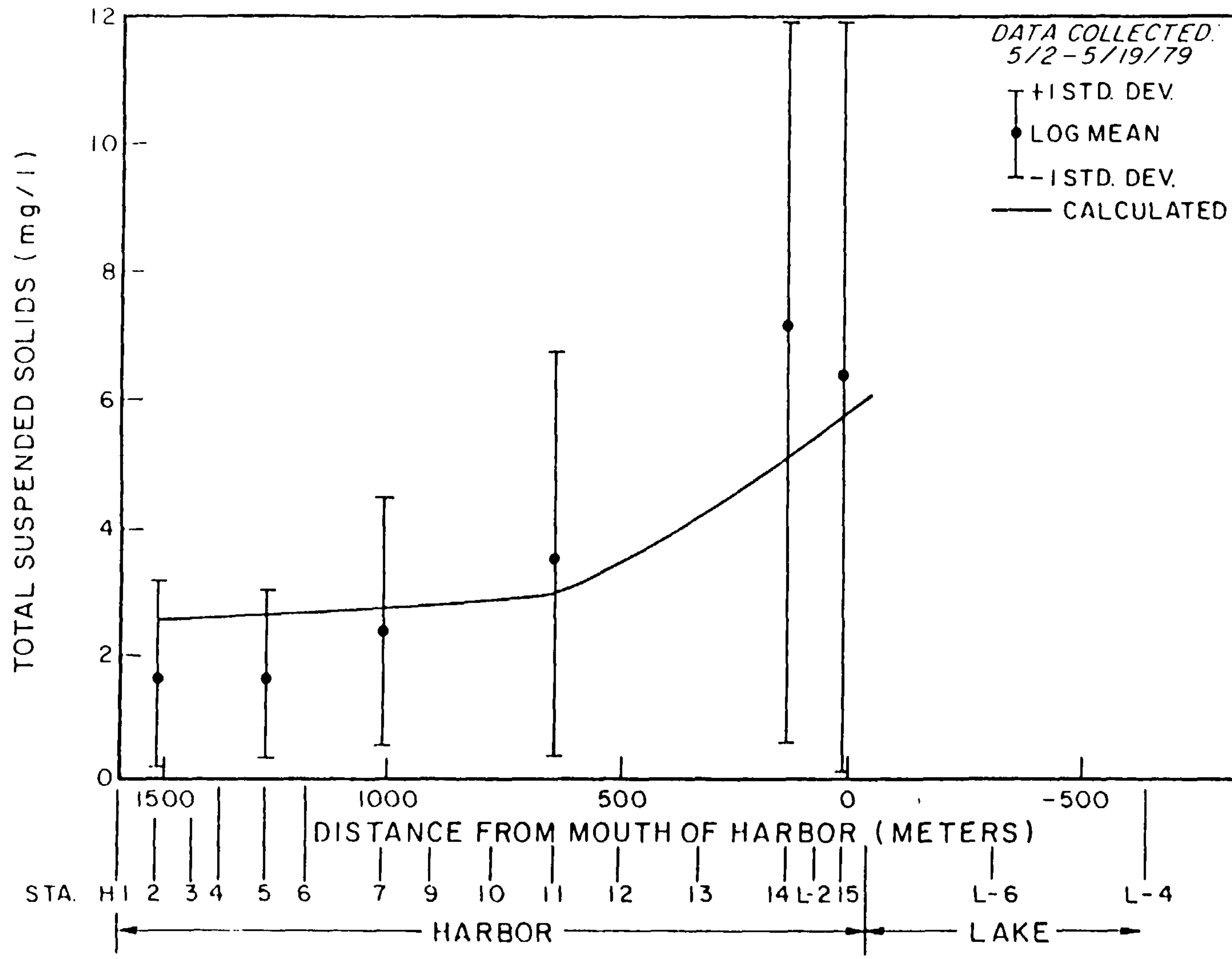


Figure 33. Calibration of total suspended solids

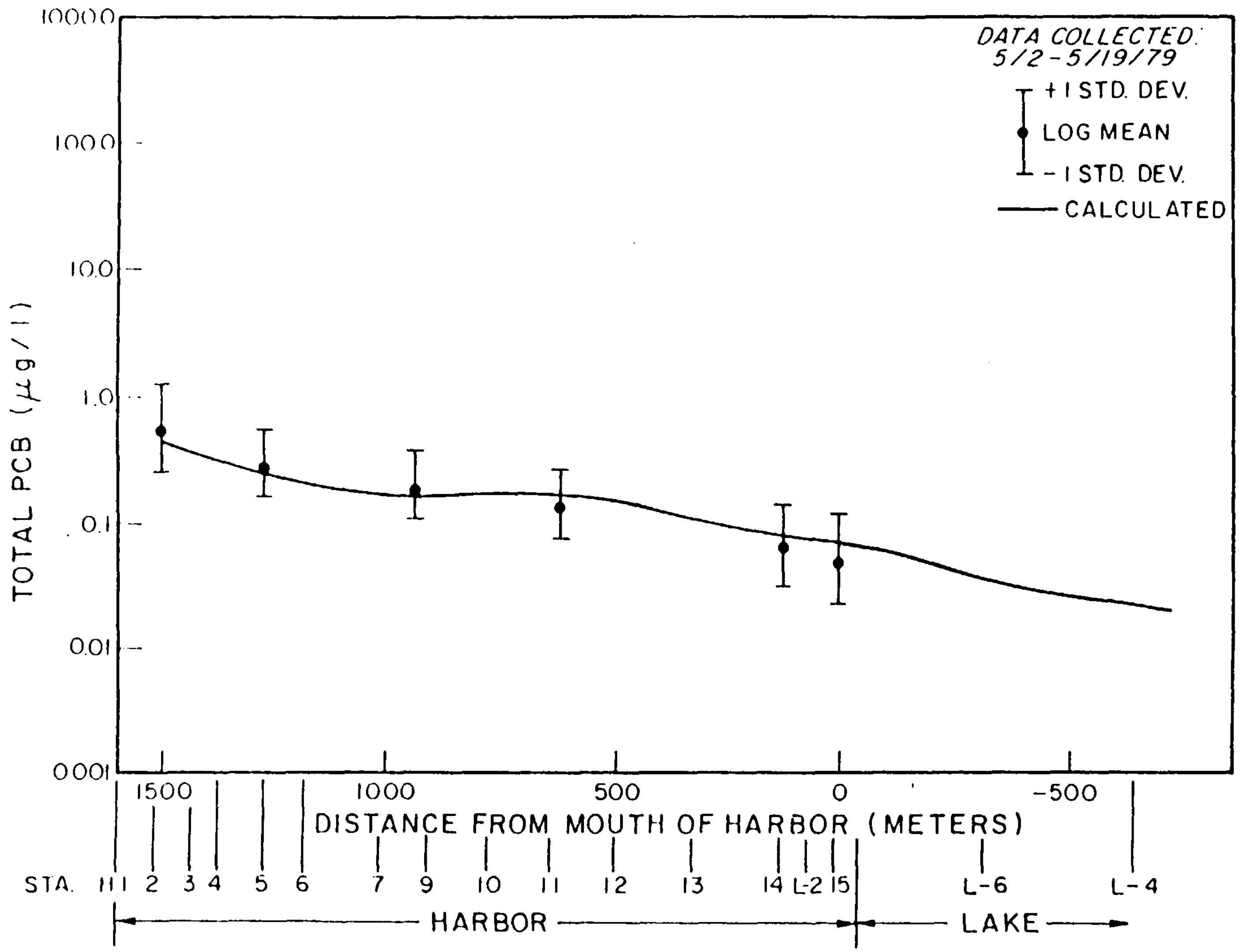


Figure 34. Calibration of total water column PCB

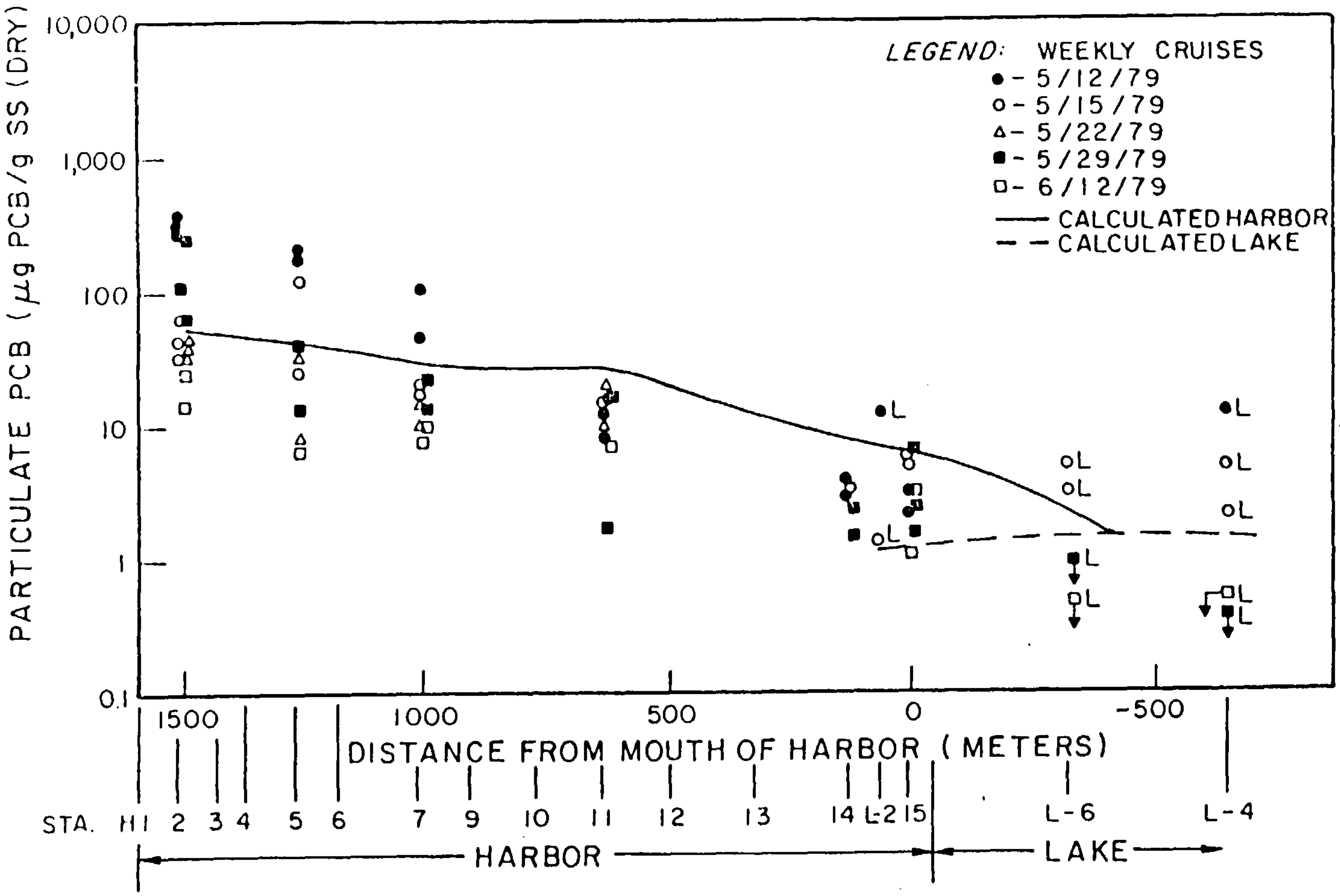


Figure 35. Calibration of water column particulate PCB

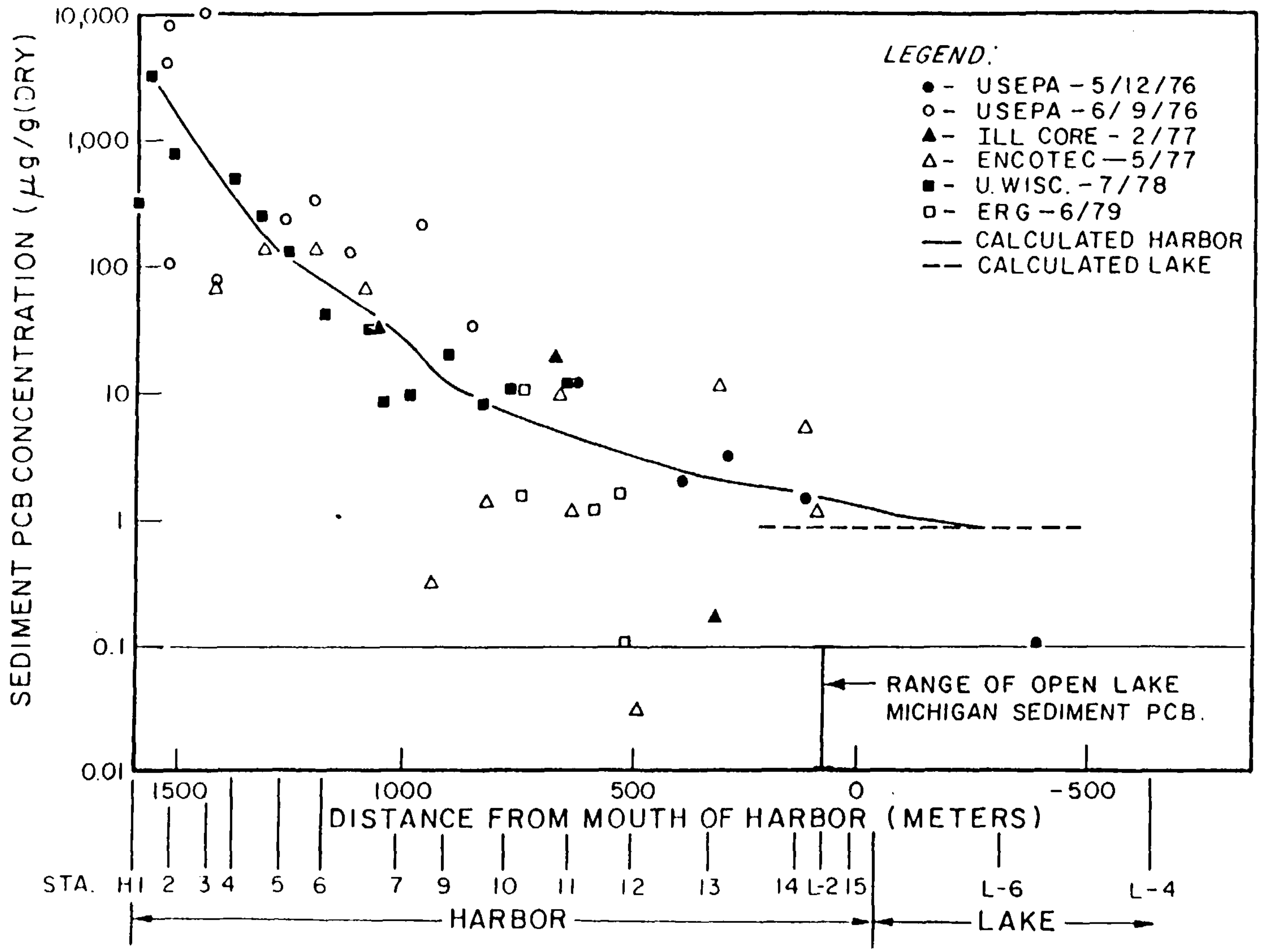


Figure 36. Calibration of sediment PCB

(

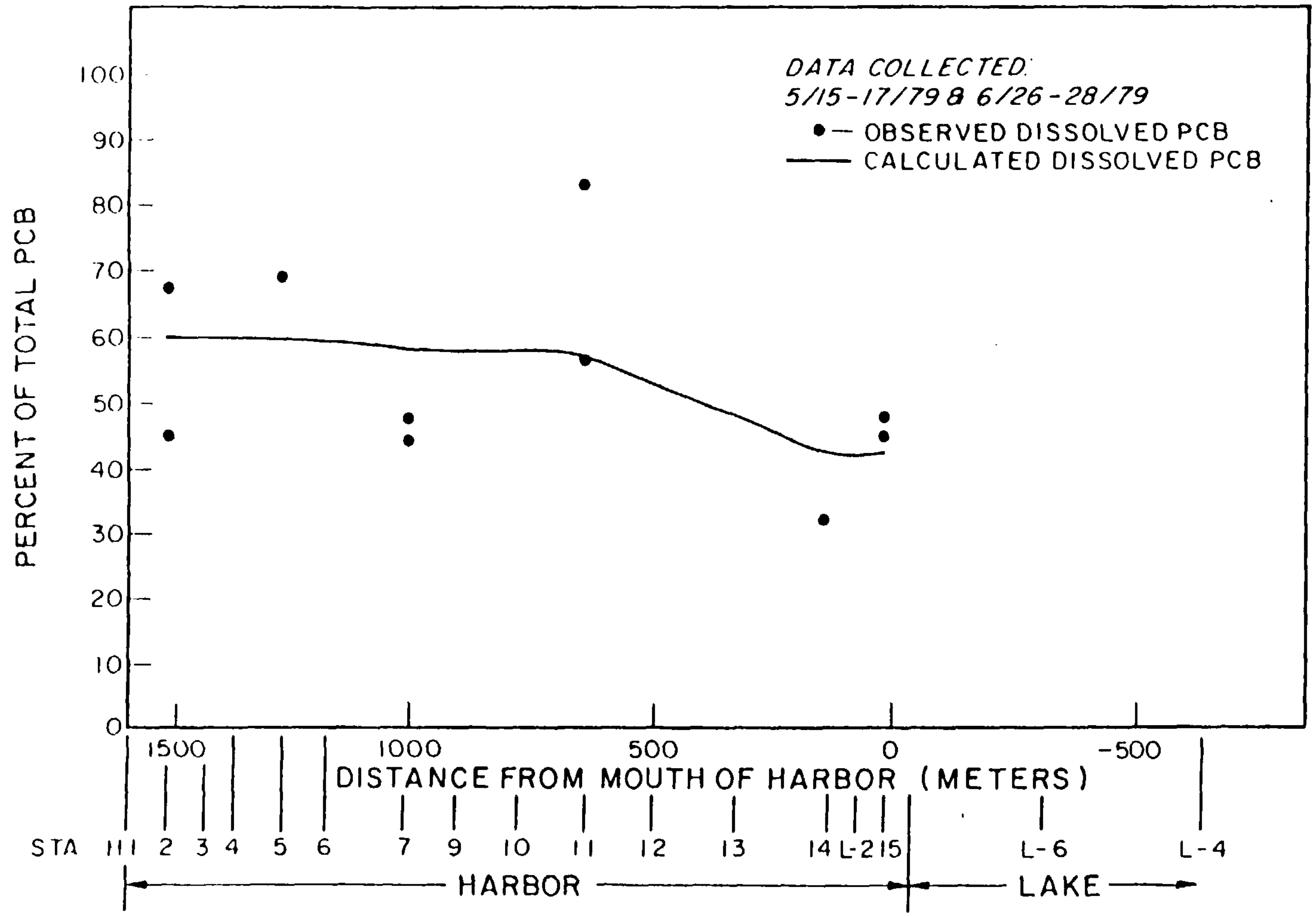


Figure 37. Comparison of calculated and observed dissolved PCB

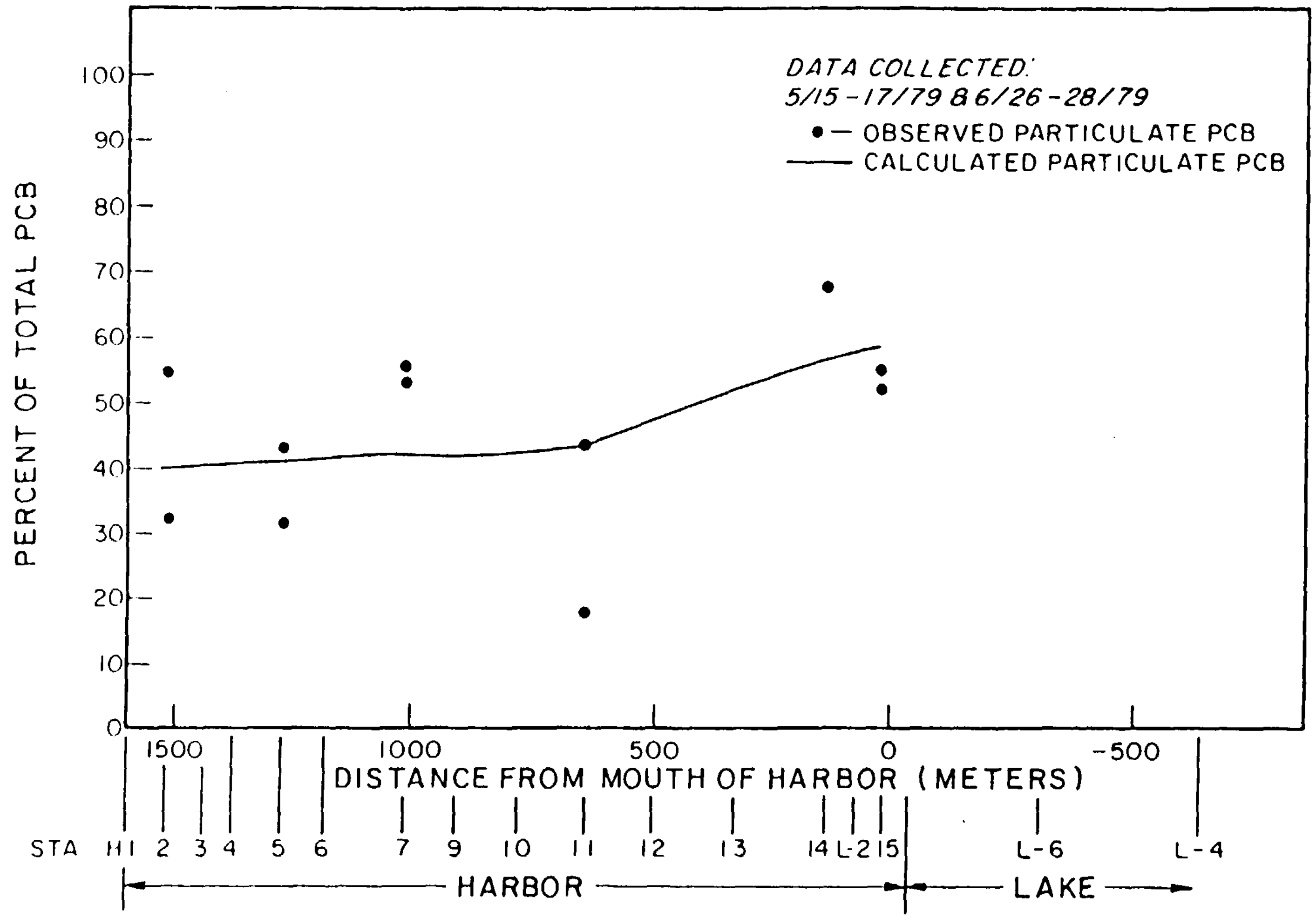


Figure 38. Comparison of calculated and observed particulate PCB

TABLE II

Parameter/Coefficient	Water Column	Sediment Layer
Horizontal Exchange	See Figure	None
Sediment Scour	None	See Figure 26
Partition Coefficient 'a' ($\mu g/g \div \mu g/l$)	250	250
Settling Velocity - (m/day)	1.0	None
Sedimentation Velocity - (m/day)	None	481×10^{-6}*
Decay Rate /(day^{-1})	0.0	0.0
Evaporation (m/day)	0.0	0.0
Porosity	1.0	0.667

*Dependent on sediment depth selected.

profiles which presently exist in the sediment bed. Consequently, the sedimentation velocity cannot be uniquely specified which in turn precludes selecting a model sediment bed depth which is compatible with the time scales under evaluation. Since recent data are unavailable, a bed depth of 20 cm was selected. This then defined the sedimentation velocity. While this problem has little or no impact on analyses performed in the water column, an evaluation of the long term (years) fate of PCB in the bed sediment is not possible.

On the basis of the calibration, it is felt that the model reproduces the observed distributions of PCB reasonably well and is an adequate representation of the prototype, especially with regard to the water column.

SECTION 7

MATHEMATICAL MODEL OF THE NORTH DITCH

In order to quantify the impact of the PCB-contaminated sediments of the North Ditch on Lake Michigan, a mathematical model for the North Ditch was prepared. The model contains the same kinetics for PCB as the model of the Waukegan Harbor (see Section 7). The geometry and transport, however, have been changed to reflect the characteristics of the North Ditch. Figure 39 shows the segmentation of the ditch for the purposes of the model.

The data background on which the model can be calibrated is very limited. There are only two occasions March 30, and April 11-12, 1979, for which there are spatial data and then only for the extreme upstream and downstream ends of the Ditch. Because of the prevailing backwater condition at the downstream end, the April 11-12 event requires a more detailed analysis for which time did not permit.

The model was first applied to simulate the June to October data on a steady state basis. The average measured flow of 0.46 cfs was used and the values of the vertical exchange (scour) were set to the same, ($1\text{-}3 \times 10^{-5}$ m/d), values of the inner Harbor (Slip #3) segments in the steady state simulation of the Harbor. Since there were no loads the model is driven by the contaminated sediment of the bottom. The degree of contamination used in this simulation was the PCB concentration in the first 1-foot sediment layer (ENCOTEC, 1977). The grab surface samples were not used in this steady state simulation because the effect of the storms between the time of collection of those samples (June 1976) and the simulated period (June to October 1979) is most likely to have altered radically the top surface of the sediment rather than 1 foot deep layer of it. All PCB boundary conditions were set to zero. The dispersion coefficient which is a measure of the exchange between the ditch and the lake was assumed to be the same in the ditch and harbor model. The lake PCB concentration was set to zero. The calculated flux of PCB from the ditch to the lake will therefore be somewhat conservative. The remainder of the parameters are given in Table III.

The comparison between the calculated and observed values of suspended solids and total PCB concentration at the downstream end are given below:

	Observed	Calculated
Suspended Solids (mg/l)	6.5 ± 2.7	6.7
Total PCB (μg/l)	6.95 ± 1.54	7.74

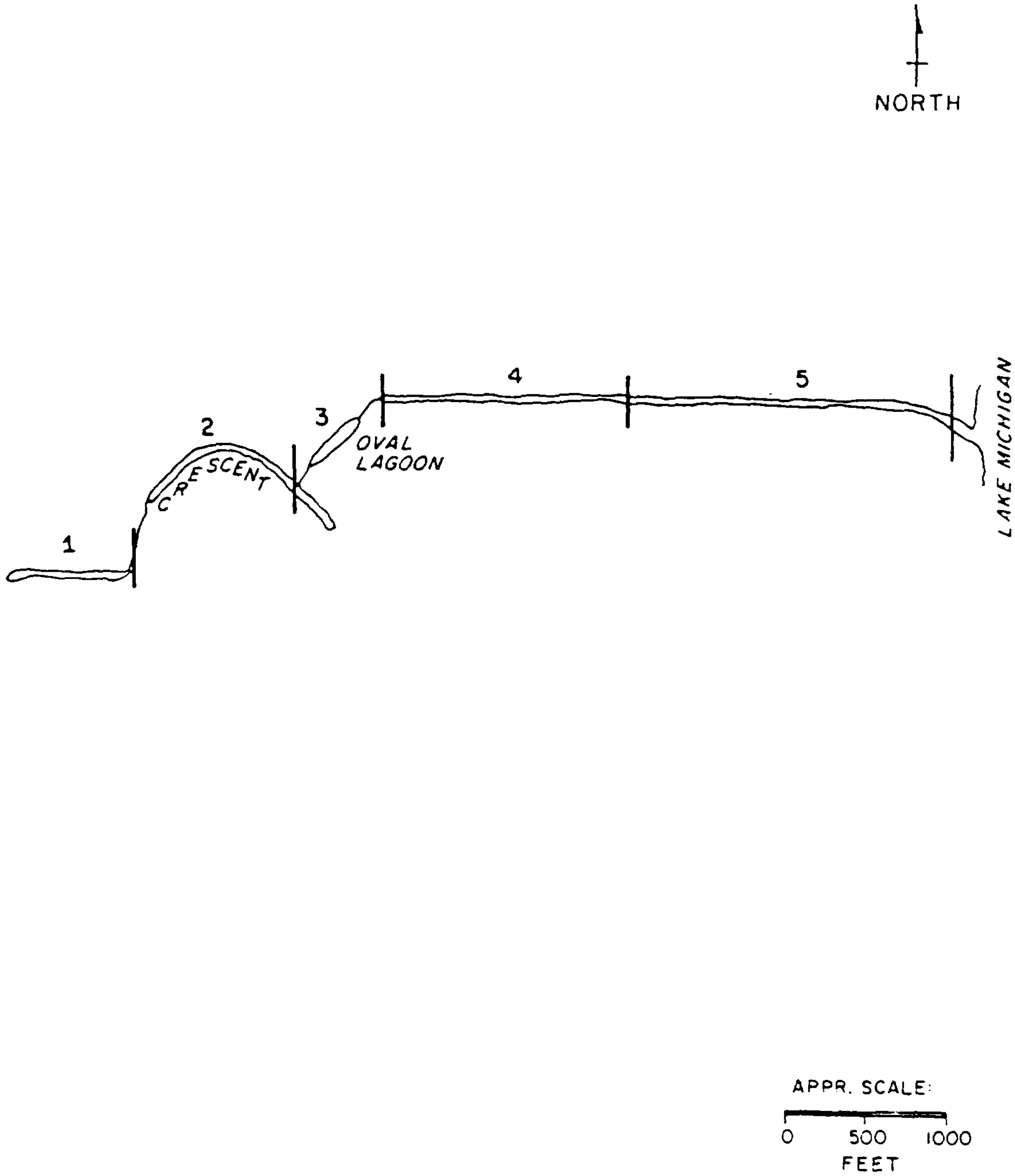


Figure 39. Segmentation of mathematical model
of North Ditch

TABLE III

Parameter/Coefficient	Water Column	Sediment Layer
Horizontal exchange-(m^3/d)	410	None
Partition Coefficient($\frac{\mu g/g}{\mu g/l}$)	250	250
Settling Velocity - (m/d)	.3	None
Sedimentation Velocity - (m/d)	None	481×10^{-6}
Decay Rate (1/d)	None	None
Evaporation (m/d)	None	None
Porosity	1.0	0.65

The flux of the PCB to the lake can also be calculated as .02 lb/d (.009kg/d) or for the June to October period .02 lb/d x 150d = 3 lb or 1.4 kg of PCB transported to the Lake on the average.

As in the case of the harbor, the model was used to simulate a high runoff event. The increased scour was reflected by increasing the value of the vertical exchange (scour) by one order of magnitude. The increased runoff flow was set at 1.5 cfs which was the "average" flow during the March 30, 1979 event. The remaining parameters retained their previous values. The results of the simulation are shown in Figure 40. Insofar that the spatial coverage of the data is quite sparse, and that the event is treated as a single constant event during the time of runoff, the validation of model may be lacking in rigor.

A time variable simulation of the March 30, 1979 event was also performed and the results are shown in Figure 41. In Figure 41A the discharge at the Footbridge was represented by a 2-hour storm discharge of 4 cfs which was then reduced to 0.5 cfs. The scour was increased by a factor of 500 and the settling velocity by a factor of 10 relative to their values of the steady state simulation. This is consistent with the fact that during a strong storm event, the shearing stresses at the sediment water interface increase so as to cause the resuspension of sediment with large particle-size diameters which in turn have higher settling velocities. In view of the fact that there were no particle size fractionation analyses performed on the suspended solids data the values of the settling velocities should be viewed as average values applied to the aggregate of suspended solids. In that sense, the increase in the settling velocity for March 30, 1979 time variable simulation can be interpreted as a shifting to higher values of the average diameter of the suspended solids aggregate. Figures 41B and 41C show the model calculation with the available suspended solids and total PCB concentrations at the Footbridge.

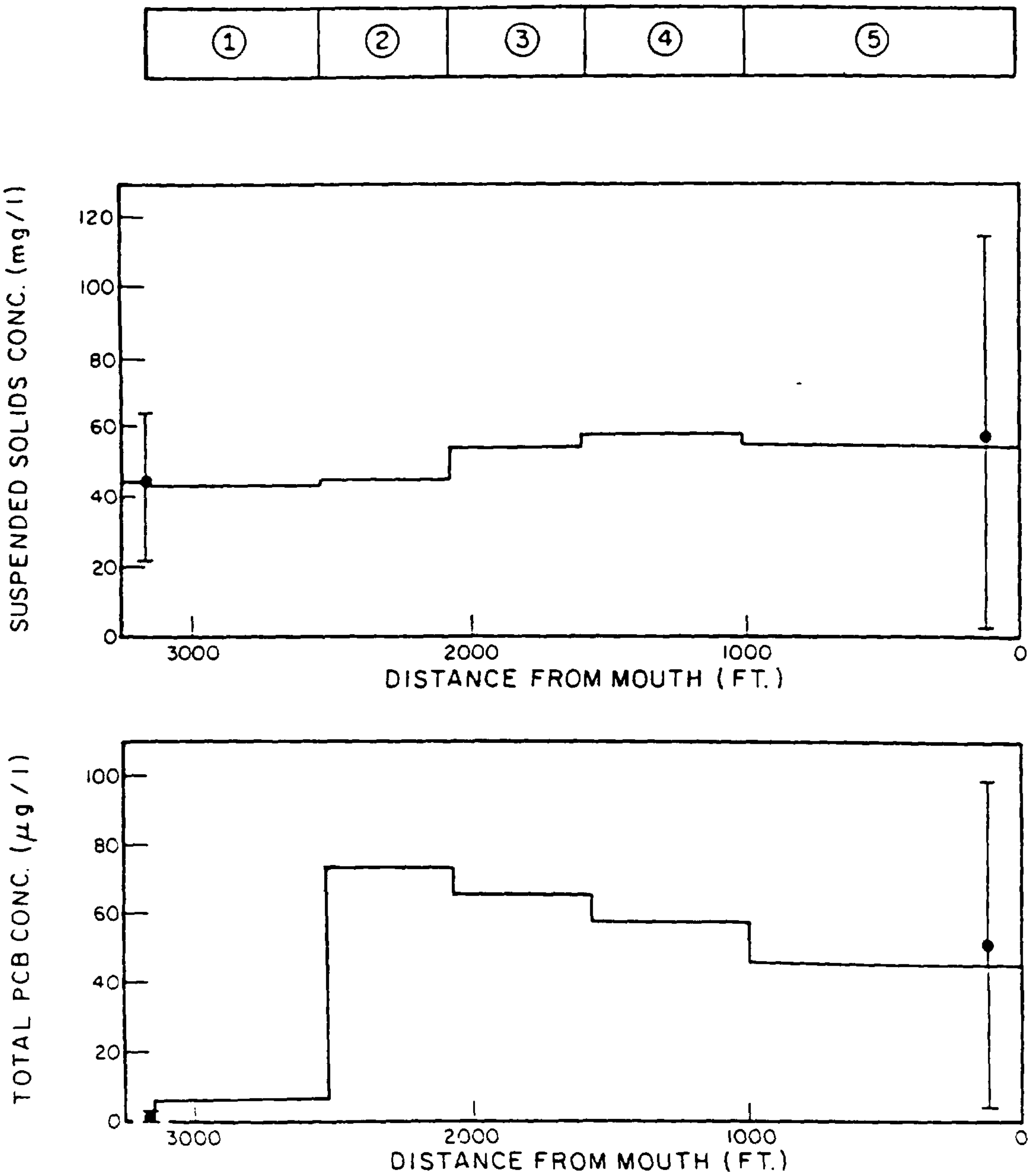


Figure 40. Model simulation of the March 30, 1979 Event North Ditch

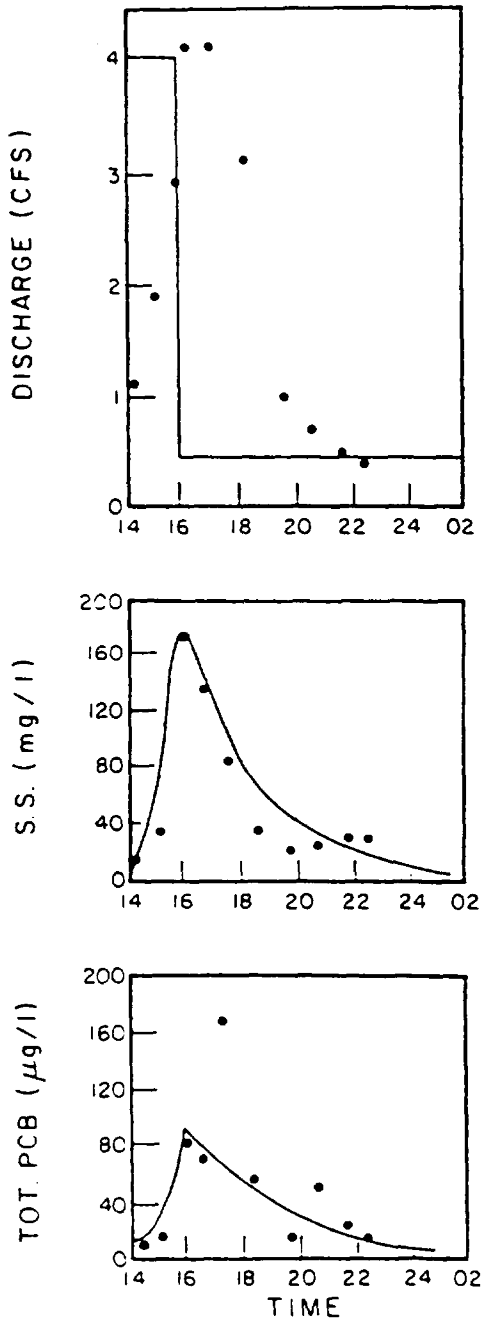


Figure 41. Time variable simulation of the March 30, 1979 Event (Data of Footbridge)

SECTION 8

PRESENT DISCHARGE OF PCB FROM HARBOR AND DITCH TO THE LAKE

Harbor

The hydrodynamic transport regime was established by the chloride and dye study calibrations. The dispersive flow predominates and is equivalent to approximately 4 m^3/sec at the mouth of the Harbor. This exchange represents the movements of water produced by wind driven currents, tidal effects, etc. When compared to the dispersive transport, the impact of an advective flow of less than 0.1 m^3/sec resulting from cooling water withdrawals is insignificant.

When the equivalent dispersive flow is combined with the gradient of PCB at the mouth of the harbor, as shown in Figure 34, the transport of PCB is calculated to be 4 kilograms per year out of the Harbor while the net flux of suspended solids is approximately 460,000 kg/year into the Harbor. It should be pointed out that the direction of the net flux of suspended solids (into the Harbor) is in agreement with actual conditions observed in Waukegan Harbor since periodic dredging must be performed to maintain channel depths. As indicated earlier during discussion of the kinetic calibration, the total exchange of PCB between the Harbor and the Lake is about equally divided between dissolved and particulate forms. These fluxes are presented schematically by Figure 42.

Figure 43 shows a map of the area with concentration contours representing model calculations of present conditions. From this, and as indicated by the calculated net flux of PCB out of the Harbor, it is apparent that the "sphere of influence" of Waukegan Harbor extends out into Lake Michigan for some distance. For example, the region enclosed by the .020 μg/l contour could result in fish PCB concentrations of greater than 5 μg/g based on the bioaccumulation factor obtained in section 9.

It appears that, periodically, conditions occur which essentially flush out the Harbor. Such a period may have been observed in mid-May 1979 when, as indicated earlier, the concentration of chlorides and PCB dropped dramatically over a four day period. Based upon the mass in the Harbor associated with the calculated profile shown in Figure 34 and assuming a "flush out" occurs as frequently as every two weeks, such phenomena would result in the release of an additional 5 to 6 kilograms of total PCB per year to Lake Michigan. It is likely, therefore, that Waukegan Harbor presently accounts for a loading to Lake Michigan of about 10 kilograms per year.

It can be hypothesized that, periodically, storms or other phenomena occur which cause disturbances in the water column

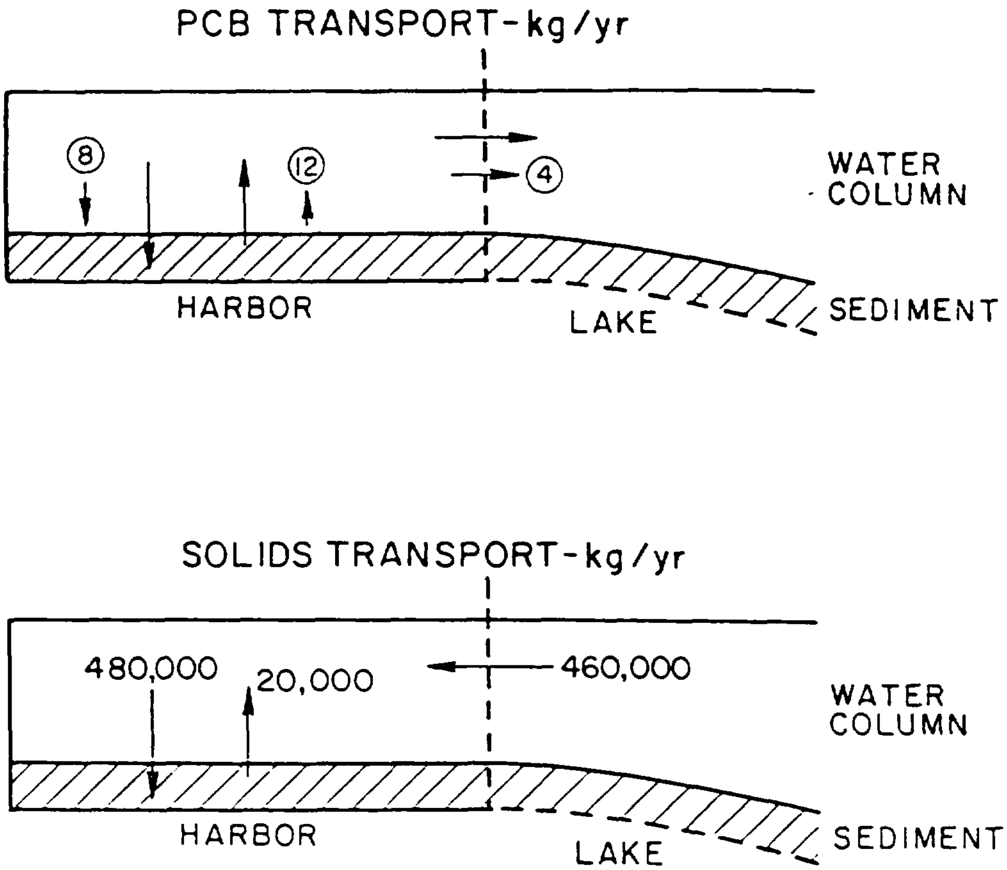


Figure 42. Flux of PCB and Suspended Solids

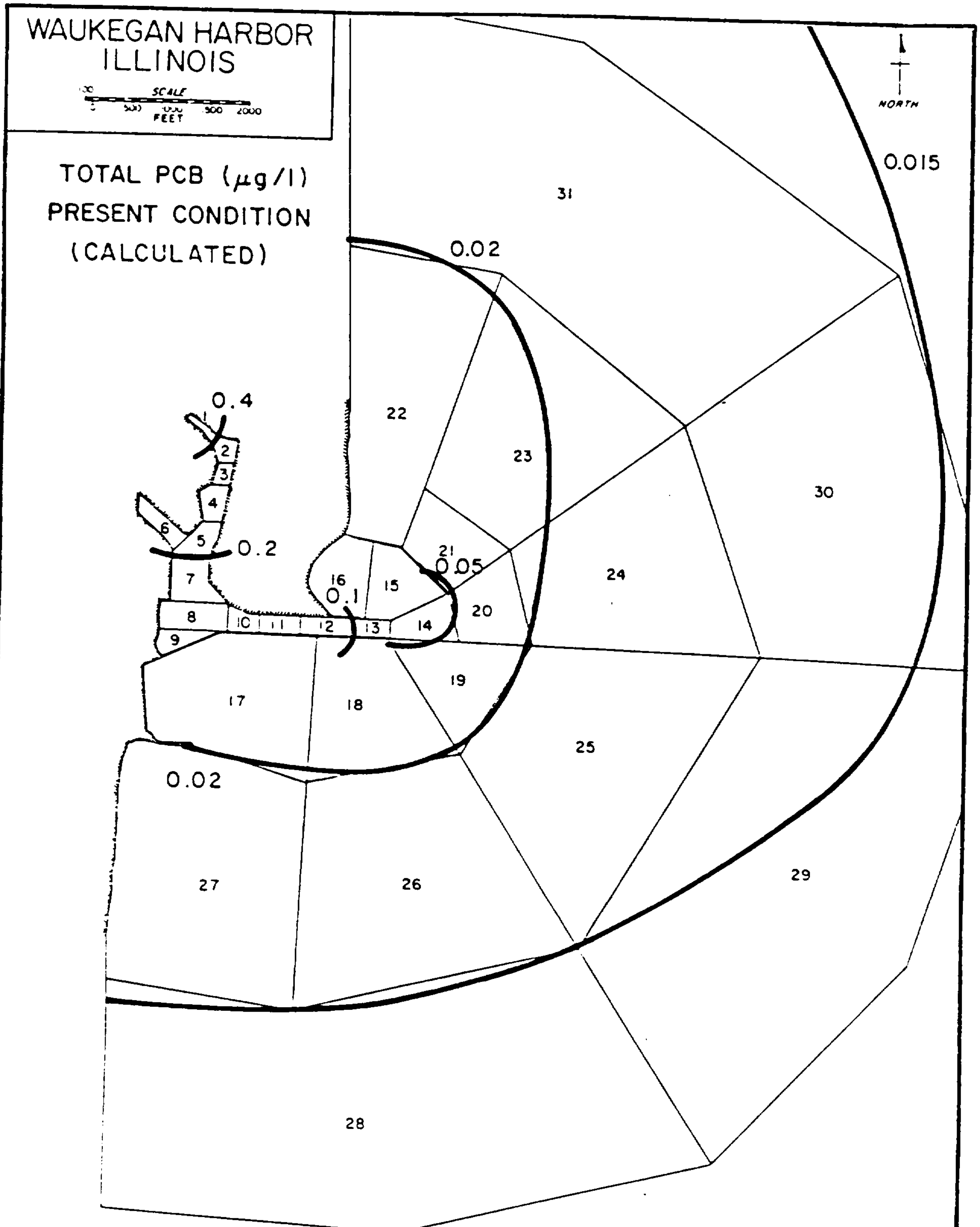


Figure 43. Calculated water column total PCB concentrations
Present condition

which result in greatly increased resuspension. A simulation of such a disturbance was performed. Resuspensior was increased, everywhere in the study area, for one day by an order of magnitude from that used in the final calibration. This might be similar to the impact of a storm on the water column. The results of this simulation, presented in Figure 44, show that there is little impact upon suspended solids concentrations in the inner Harbor during the storm. An increase in suspended solids in the Harbor is not produced until several days after the storm when increased solids levels in the Lake are transported into the Harbor.

The impact of the "storm" on PCB concentrations in the inner Harbor, however, is marked. Nevertheless, the mass of PCB which is discharged to the Lake is small. The large increse in PCB concentration in the inner Harbor produced by the storm is greatly reduced through settling by the time the mouth of the Harbor is reached. Consequently, only additional tenths of kilograms of PCB are discharged to Lake Michigan from the Harbor due to such occurrences.

The modeling framework can be used to also estimate the relative amount of PCB that may have been discharged to the Lake when PCB's were being used in the OMC plant approximately during 1955-1971. A simulation was therefore performed under the conditions of suspended solids and bed sediment transport during the calibration tests discussed in Section 7. A fixed discharge PCB load of a constant yearly input was used in the model. This is in contrast to the present situation where the only onput is grom the contaminated sediment. The constant external load was used to determine the fraction of a given amount of discharged PCB that entered the sediment and the fraction that was discharged to the Lake. The result of this simulation indicated that during the time of PCB discharge to the Harbor by the plant approximately 38% escaped to the Lake and about 62% was transported to the sediment. It should be noted that these percentages do not take into account events that may have occurred during the actual discharge such as aggregation of PCB in globules whose transport may be different than the one attributed to PCB in this report. These results are utilized in Section 11.

Ditch

From the steady state and time variable simulations for the North Ditch, it becomes apparent that a reasonable estimate of PCB discharge from the ditch to Lake depends on an analysis of the frequency of the storm events.

Frequency of Storm Events. It is important to recognize that various rainfall events may occur that can lead to relatively

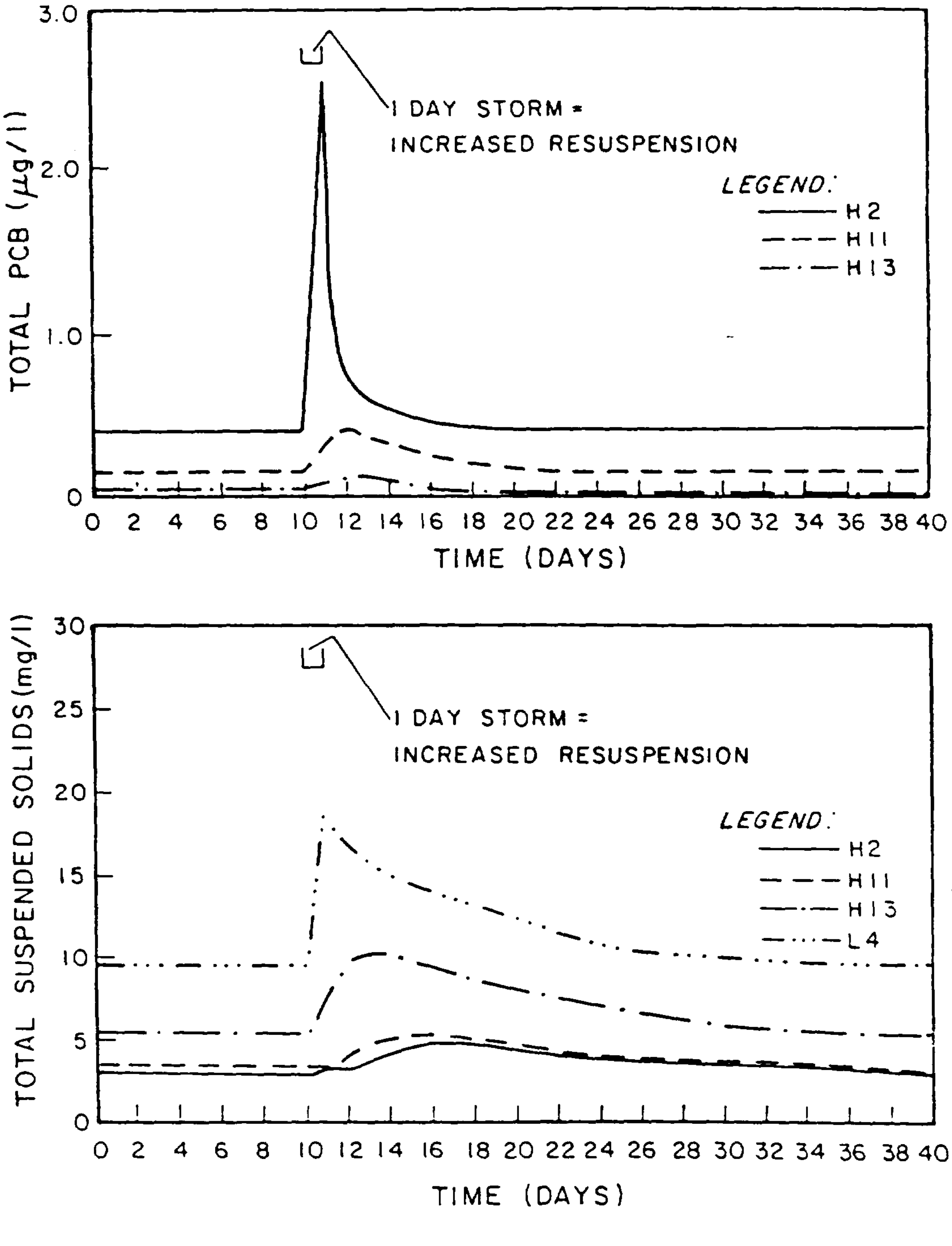


Figure 44. Impact of a storm on total PCB and total suspended solids

high volumes of runoff to the Ditch and result in elevated levels of discharge from the Ditch to the Lake. Likewise, an estimate of the expected frequency of occurrence of the event of March 30, 1979, is important since it will help to position that event in the spectrum of possible events that could occur in the North Ditch area.

The basic approach to estimating the frequency of storm events is reviewed in EPA (1976) and draws on some basic statistics related to rainfall events. The statistics are shown in Figure 45. As seen, information on rainfall intensity (in/hr or cm/hr), the duration of the storm event (hrs) and the interval between events (days) are all important quantities. Other statistics estimated for Waukegan, for Milwaukee and Chicago are given in Table IV. In addition to the statistics, the mean interval between storm events for the Waukegan area can be estimated at about 3 days, i.e., there are about 120 events/year on the average. This is consistent with the data for 1979 in the North Ditch which indicated that from June - October, there were 48 days of events which is approximately equivalent to 120 events for the entire year.

The average runoff volume per event can be estimated from the rainfall-runoff relationship

$$V_R = 3630\ C_v VA$$

where V_R is the volume of runoff (ft^3), C_v is the coefficient of runoff estimated from the 1979 data at about 0.4), A is the drainage area (acres; North Ditch at about 65 acres) and V is the volume of rainfall (in) given by

$$V = \overline{I} \cdot \overline{D}$$

where $\overline{I}$ is the average intensity (in/hr) $\overline{D}$ is the average storm duration (hr) and I and D are assumed independent. For the average intensity during 1979, the average volume of rainfall is 0.38 in/event. The average volume of runoff then is given by

$$V_R = 3630(0.41)(0.38)(65)$$

$$= 38760 ft^3\ (1041 m^3)$$

This is equivalent to a runoff of about 0.45 cfs over a day using the rainfall-runoff relationship discussed previously. Other estimates of runoff volume and flow using the rainfall statistics of Table IV are given in Table V.

The question now is "How many events of a given magnitude of volume of runoff can be expected in an average year?"

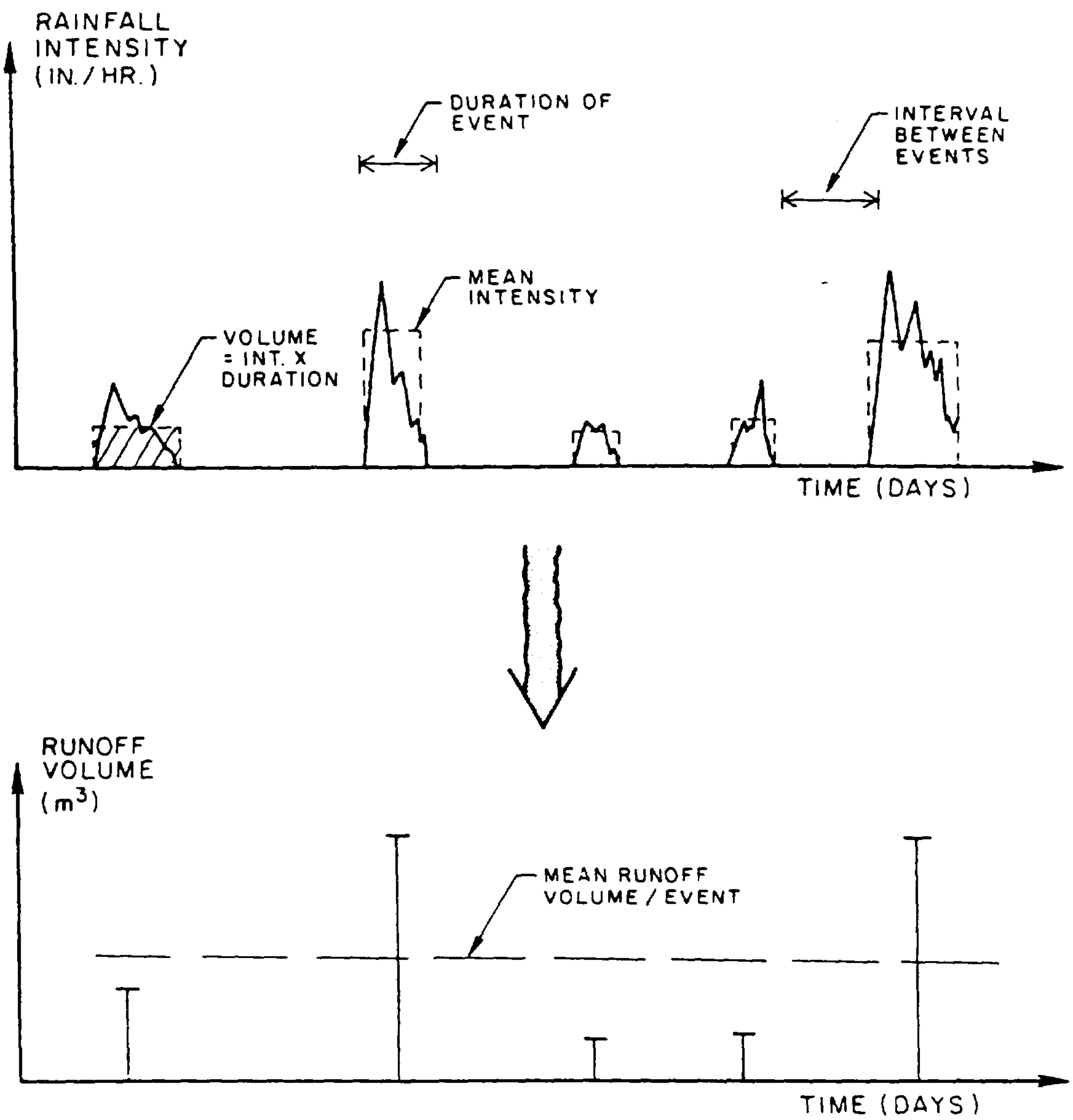


Figure 45. Definitions for Runoff Frequency Analysis

TABLE IV

RAINFALL STATISTICS OF SIGNIFICANCE TO WAUKEGAN AREA

Precipitation (in)	Waukegan[1]	Chicago[2]	Milwaukee[2]
Mean Annual	30		
Maximum Annual	42		
Annual $\geq$25% of time	35		
Maximum 1 hr.		2.8	2.2
Maximum 24 hr.		6.2	5.8

(1) Linsley, R.K. et.al., 1958. Applied Hydrology. McGraw Hill Book Company, N.Y., N.Y., 340 pp. - approximate estimate.

(2) Todd, D.K., 1970. The Water Encyclopedia. Water Information Center, Port Washington, N.Y., 559 pp.

TABLE V

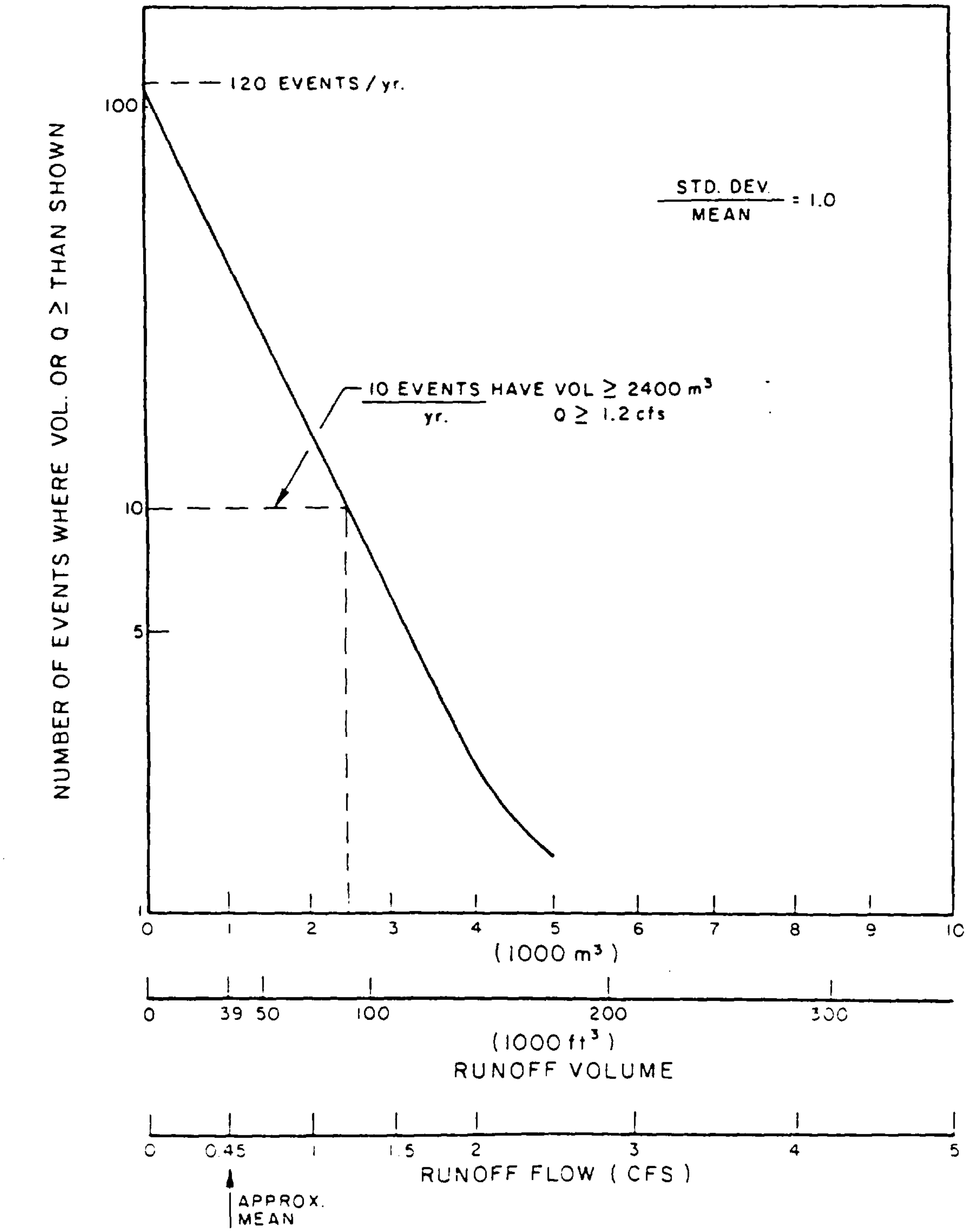
RUNOFF VOLUME AND FLOWS FOR DIFFERENT RAINFALL EVENTS

Rainfall Event	Rainfall in/day	Volume of Runoff $1000 ft^3$	Runoff Flow cfs
Maximum 24 hr.	6.0	612	7
Maximum 1 hr.	2.5	242	66
Mean 24 hr.	0.38	39	0.4

The estimation of the frequency distribution of the number of events of a given magnitude of runoff volume depends on an estimate of the ratio of standard deviation of the rainfall volume to the mean volume. This has been chosen as a volume of one since trial calculations indicated that such a volume would conserve the total volume of runoff expected throughout a year. Following EPA (1976), Figures 46 and 47 can be constructed. As shown, under the assumption of standard deviation/mean of 1.0, approximately 10 events/year would have a volume of runoff $\geq$ 89,500 ft^3 (2400 m^3) and a flow $\geq$1.2 cfs. If the frequency distribution is approximated by a discrete distribution, Figure 47 indicates that one could expect the mean runoff volume of 39,000 ft^3 to occur about 30 times/year. A series of high runoff volume events would be expected to occur once each year and one event of greater than about 186,000 ft^3 would be expected to occur. A total runoff volume of 432,000 ft^3 (12,200 m^3) represents an approximation of the upper bound of an event to be expected in any given year. Note that this is about 70% of the long term maximum daily event (Table V) from about 60 years of record. This runoff volume corresponds to a runoff flow of about 5.0 cfs. The runoff flow of 5.0 cfs therefore represents an event that is a maximum event for an average year and about 30% of the absolute maximum daily runoff to be expected over a long period of time. On the basis of this analysis, a run of the North Ditch model was prepared at 5.0 cfs for one day.

The mathematical model, as calibrated to the time variable March 30, 1979, event was therefore run with a flow of 5.0 cfs for 24 hours. The exchange with the lake was not changed. The result is shown in Figure 48. As shown, this calculation indicates that a mass of about 3 kg PCB would be released under these conditions. However, one would normally expect the resuspension velocity to increase during a maximum storm event and conversely one would also expect the settling velocity of the solids to increase. A sensitivity analysis of the 5.0 cfs - 24 hour storm was therefore indicated to determine if the estimate of 3 kg would be markedly altered by different assumptions in resuspension and settling. The result of that analysis indicated that if the settling were the same and the resuspension were doubled relative to the storm simulation of Figure 41, the estimated PCB mass released increases to 6 kg for such an event. Further increase in the resuspension is not warranted since such simulations indicate unreasonably high suspended solids concentrations even at extremely high settling velocities.

However, the steady state analysis can provide an order of magnitude calculation basis to estimate the PCB movement over the long term. To get an understanding of the PCB movement, a load of 10 lb/d PCB was introduced into seg. 2. The PCB flux to the



REF. FROM AREAWIDE ASSESSMENT MANUAL, EPA

Figure 46. Estimated frequency distribution of storm events for Waukegan Area

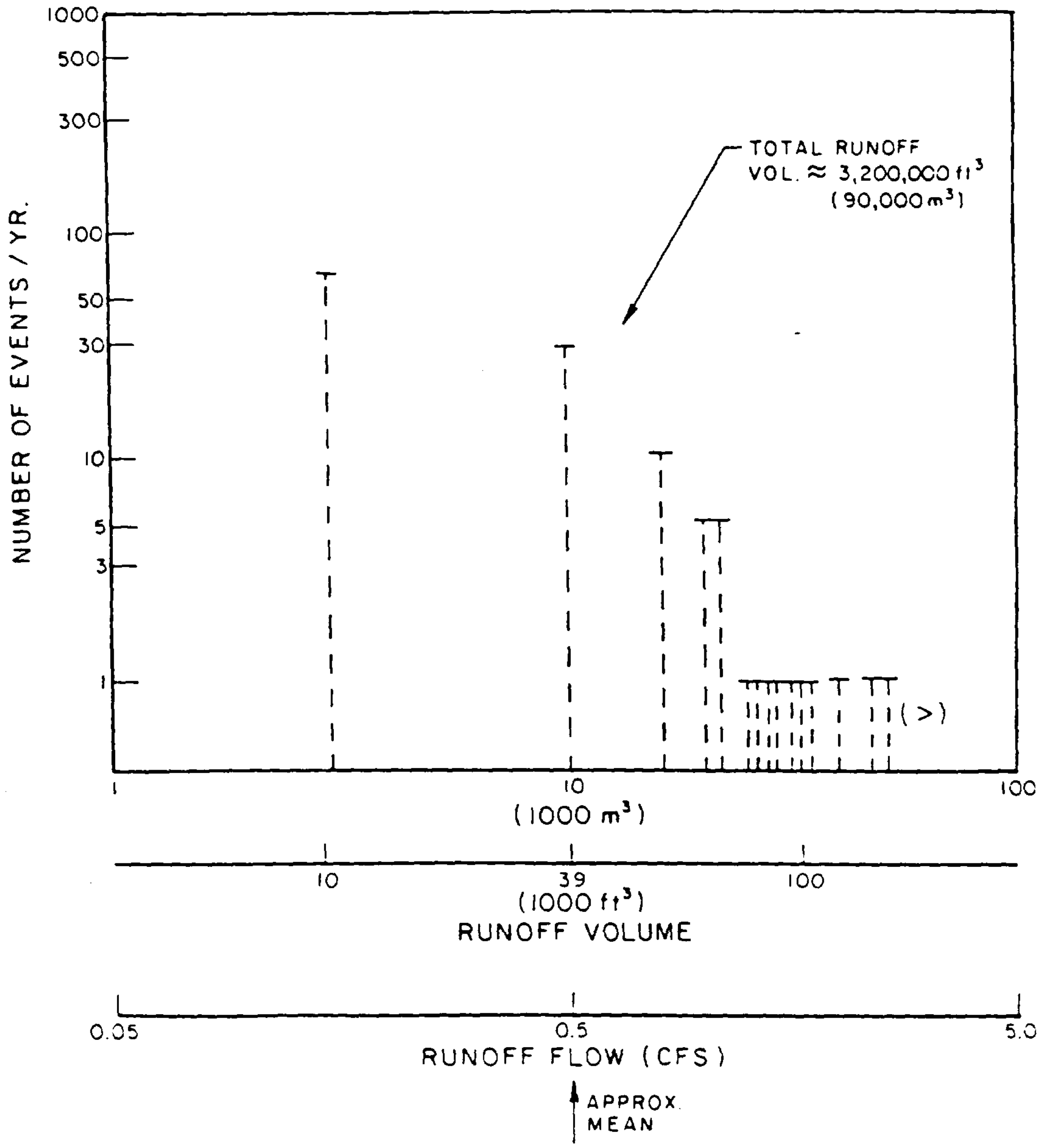


Figure 47. Estimate discrete approximation of distribution of 120 events/year

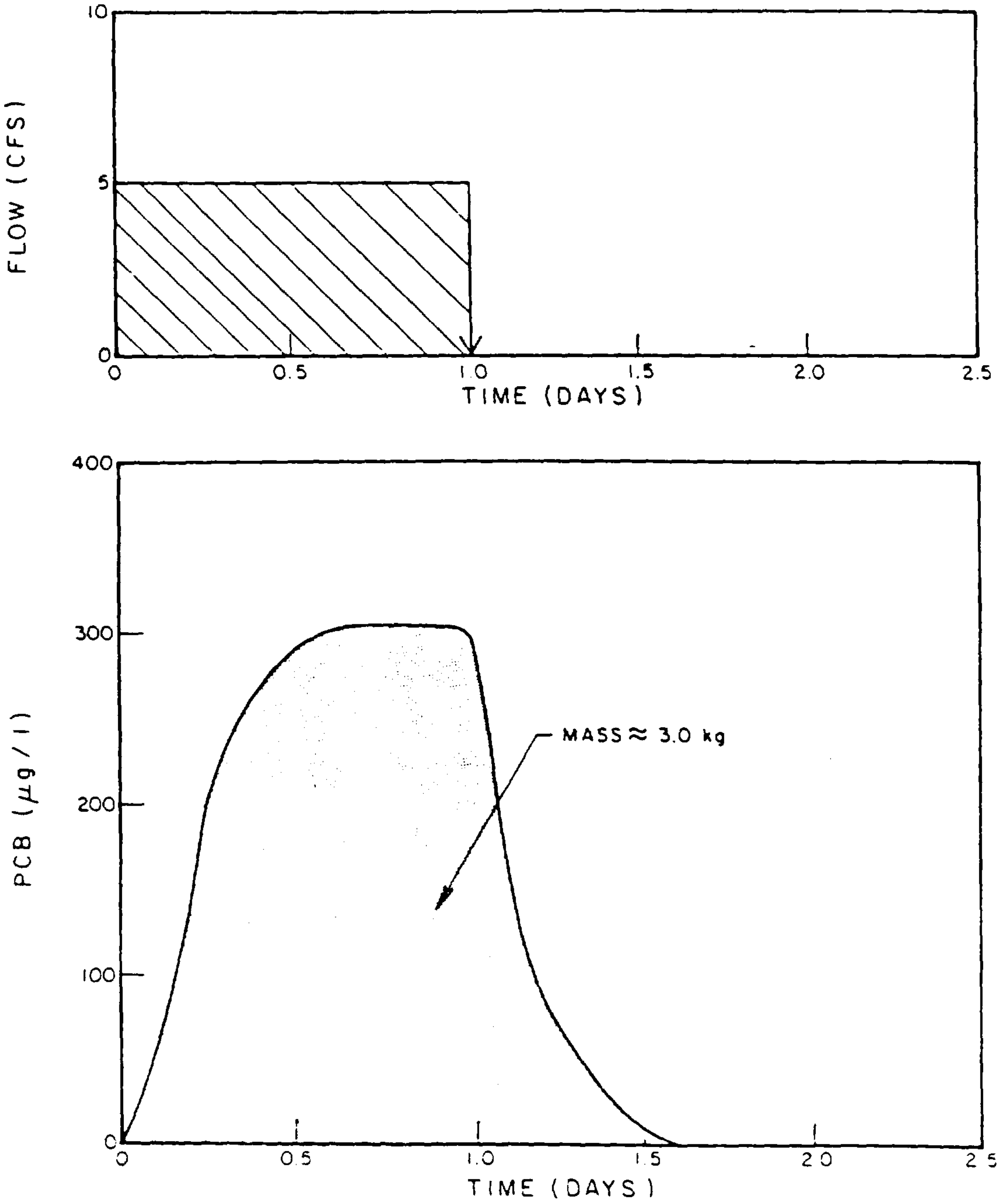


Figure 48. Simulation of 5.0 CFS for 24 HR. Storm Event to North Ditch

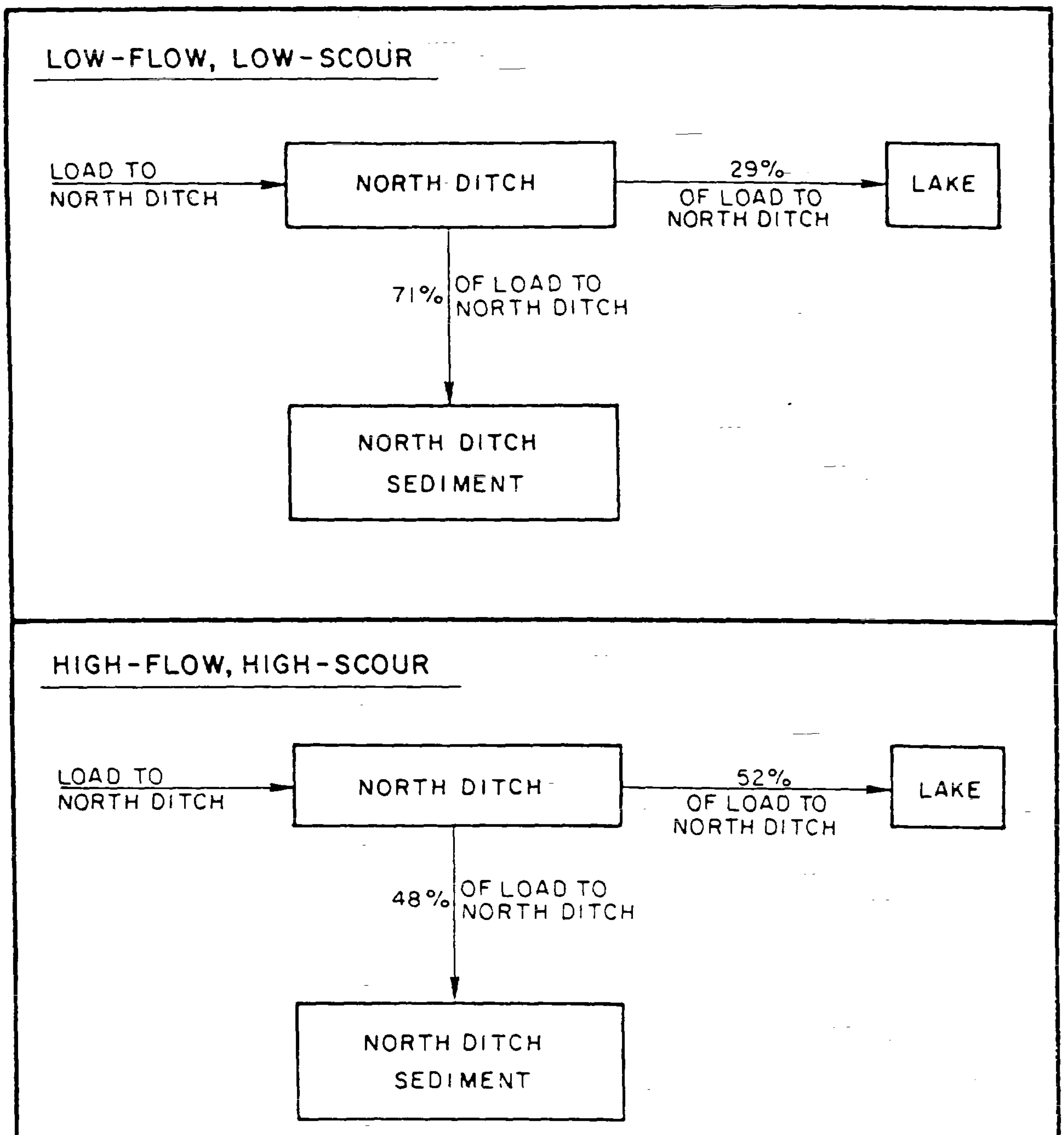


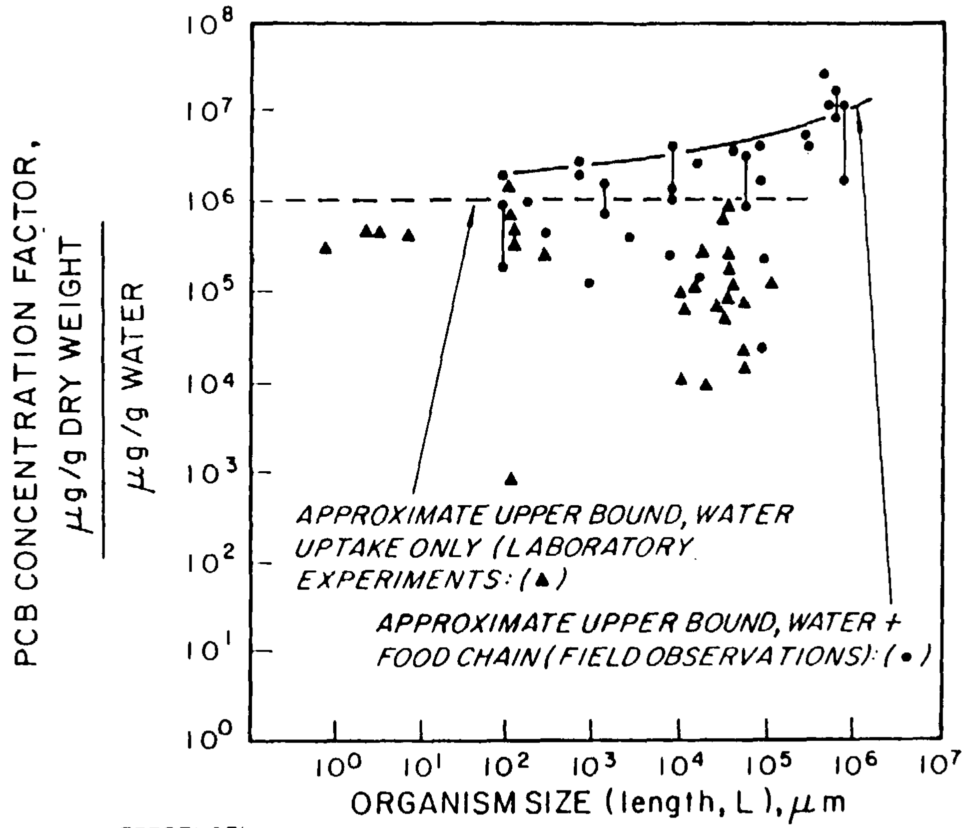
Figure 49. Load transfer to ditch sediment and Lake Michigan
(Load in Seg. 2)

SECTION 9

BIOACCUMULATION OF PCB'S

One of the major concerns of the discharge of PCB's to a system such as Waukegan Harbor is the potential for accumulation of the chemical by the aquatic food chain and subsequent potential transfer to man through intake of contaminated fish. A considerable and growing literature exists on the accumulation of PCB's by various aquatic organisms. Thomann (1980a) has compiled much of this literature with the specific aim of determining the relative amount of PCB that would be concentrated by an aquatic organism directly from the water and the amount of PCB that would be accumulated through ingestion of contaminated prey. Figure 50 taken from that work indicates the comparison of these concentration factors. The data appear to indicate a clear divergence between the amount of PCB taken up from the water only and that accumulated from both the water and the food chain. At organism sizes of about 10^5 μm (0.1 m), the small fish, the bioaccumulation factor is about $10^{6.6}$ μg/g (dry) per μg/g (water) or about 4 times higher than the factor from water alone. The difference is attributed to the predation of contaminanted prey, the low excretion rate of PCB's and a hypothesized high absorption rate of PCB from the food.

The scatter in the data indicate a range of accumulation factors depending on the species of the aquatic ecosystem. If small fish (<300 mm) are used for Waukegan Harbor in a simple two level food chain, then an approximate estimate of the bioaccumulation factor is about 630 μg/g per μg/l PCB dissolved in the water column. Applying this factor to the range of dissolved PCB discussed in the preceding section permits the calculation of the fish PCB concentration range. This calculation is shown in Figure 51 where it should be noted that the range is only approximate and may vary depending on the actual ecosystem structure and the actual dissolved PCB levels available for uptake. Some data collected on fish body burden during August 1978 are also indicated on the plot. The data are plotted at the mid-point of the areas where the fish were collected. As can be seen, the calculated range incorporates the bulk of the observed data. Of the three lower values, one represents PCB's in the alewife which may have migrated into the Harbor from the Lake. The open Lake range is indicated as 1-10 μg/g. The calculation indicates that the expected body burden of PCB's may range from about 100 μg/g to about 5 μg/g for the small fish. The present operable Food and Drug Administration Section level for the edible portion of fish is 5 μg/g and a proposed, but postponed level is 2 μg/g. It should be noted that the data PCB body



REFERENCE:
AFTER THOMANN (1980)

Figure 50. Evaluation of concentration factors

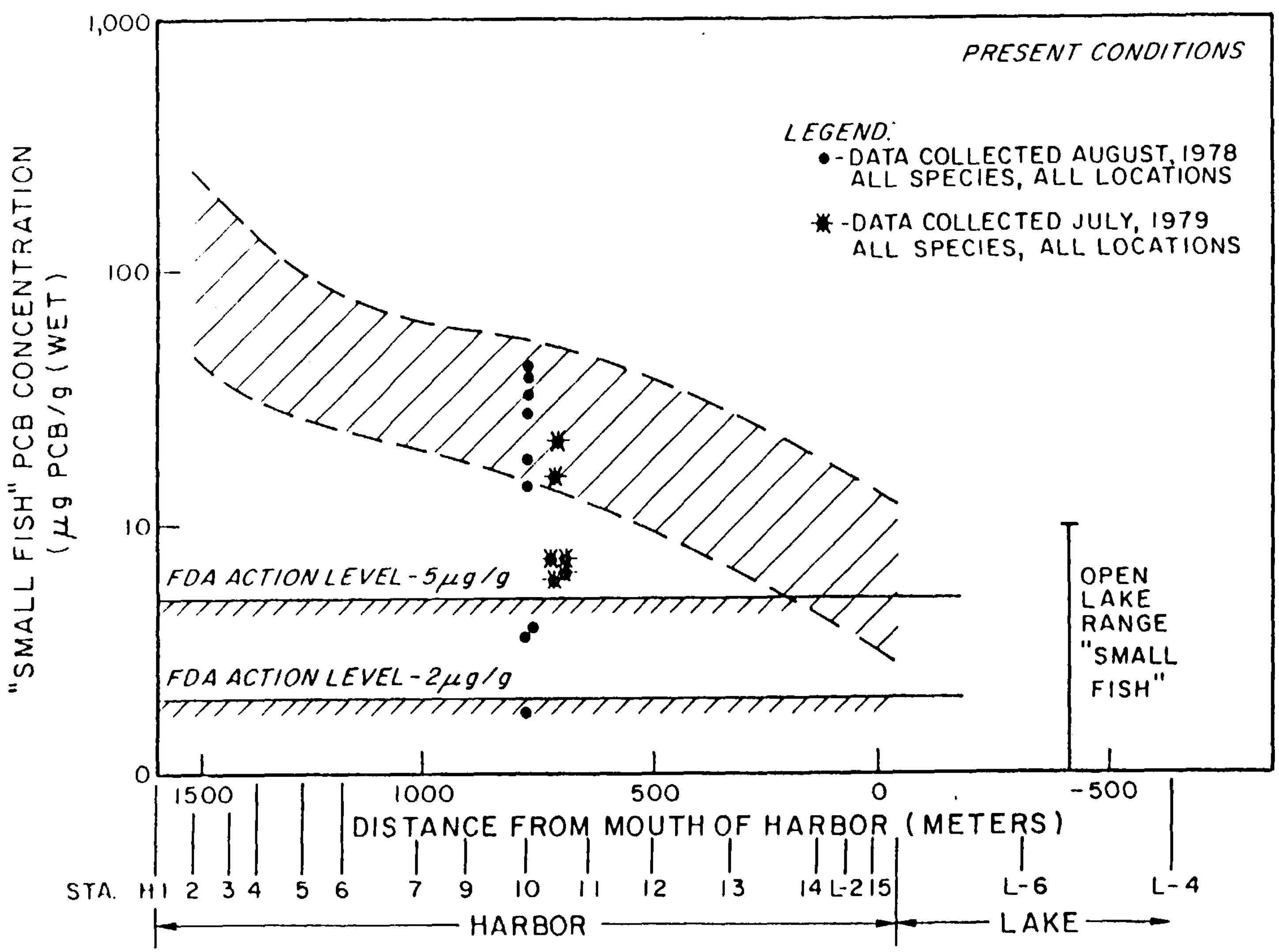


Figure 51. Estimated fish PCB concentrations for "Small fish" (< 300 mm)

burdens are given on a whole-body basis whereas the FDA levels are given on an edible portion basis. The present levels of PCB in Waukegan Harbor therefore result in concentration in the fish that exceed FDA levels by a factor of at least 10 for significant regions of the Harbor. Additional data on the PCB concentration in resident and migrating fish should be collected, however, to further confirm this conclusion.

SECTION 10

PCB PRODUCT LOSS AND FLUX TO LAKE MICHIGAN DURING USE OF PCB

An important aspect of the entire question of the discharge of PCB is the fraction of the amount of PCB that was purchased that was lost to both Waukegan Harbor and the North Ditch. Although this product loss could be estimated from consideration regarding the use of the purchased PCB in the industrial plant itself, a computation is presented here that estimates the product loss to the Harbor/Ditch system as well as the loss to Lake Michigan during the time of PCB use.

Figure 52 shows the principle components of the fate of PCBs in the Harbor/Ditch system. Of the total quantity of PCB purchased, a fraction was discharged to the Harbor and Ditch. The sediment of these two water bodies therefore represents a deposit of PCB resulting from the long term discharge. The computational scheme discribed earlier in the sections in the mathematical model of the Harbor and Ditch permits one to calculate the percentage of the amount discharged that entered the Lake and conversely the amount that entered the sediment. With the estimates of the PCB in the sediment and the fraction of the amount discharged that found its way to the sediment, an estimate can be made of the moss of PCB that was discharged during usage. If the total quantity of PCB that was purchased is known then an estimate can be made of the percentage of purchased PCB that was discharged to the Harbor/Ditch system.

Therefore, prior to making an estimate of the PCB loading to either the North Ditch, Waukegan Harbor or eventually Lake Michigan, an estimate of the PCB-product usage by the Outboard Marine Corporation must be made. Table VI gives the estimated yearly usage of various PCB and non-PCB mixtures as obtained from plant information. Figure 53 is a temporal plot of the same data. Assuming that the type of product used during 1955-1958 contained PCB, then the total PCB-containing usage for 1955-1972 amounted to 11,660,000 lbs (5,294,700) kg. If the unknown type is excluded, the usage of PCB-containing product for 1959-1972 is 9,560,000 lbs (4,341,300 kg). The average annual total PCB product usage for 1955-1970 is 724,000 lbs/yr (328,700 kg/yr) as shown in Figure 53.

The modeling calculations for the Harbor and Ditch can be examined to determine the relative flux discharge to the Lake from either the Harbor or Ditch. For the latter, the low-flow, low-scouring case can be coupled with the discharge into Slip #3 of the Harbor. For example, if one considers the flux from the Harbor to be due to a discharge into slip # 3 and the flux from

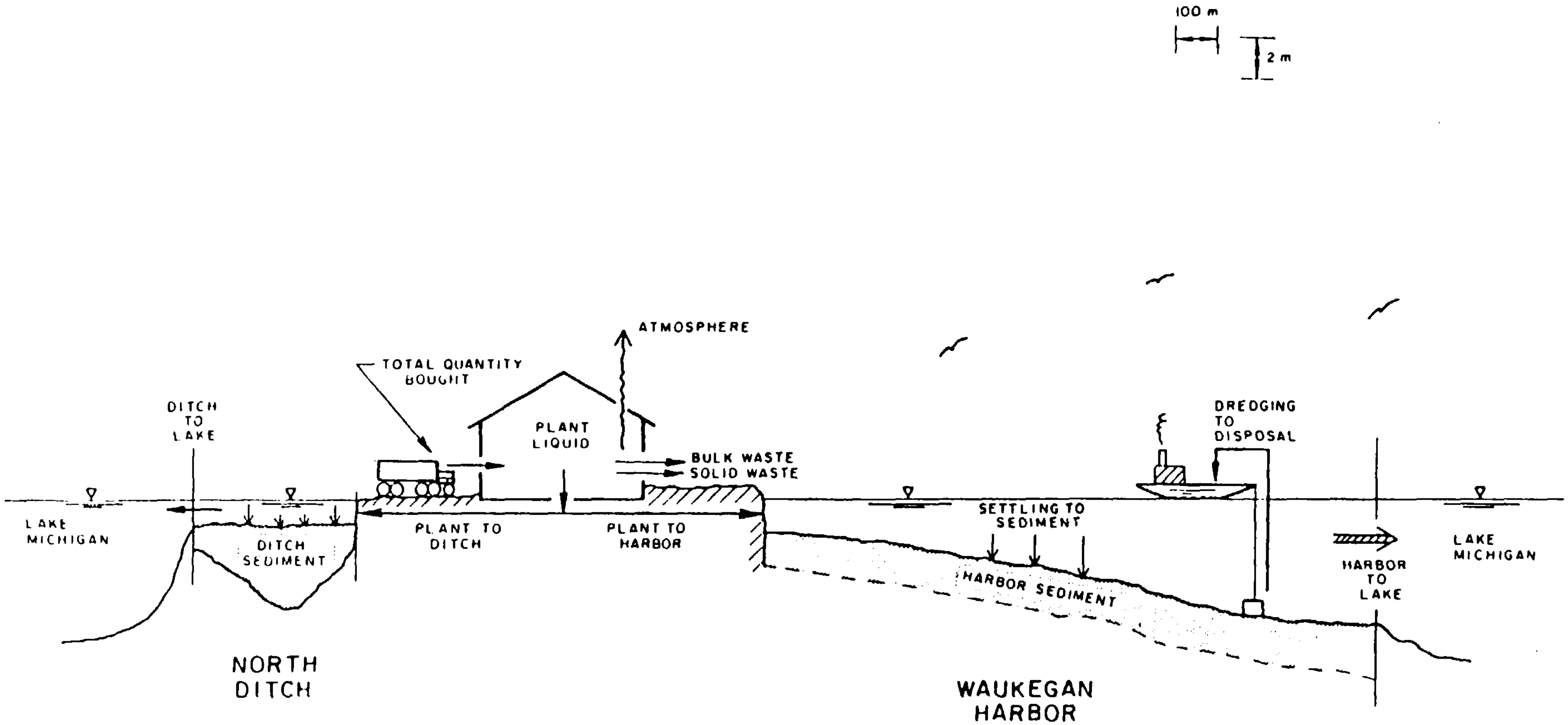


Figure 52. Elements of PCB Budget for Waukegan Harbor and North Ditch

TABLE VI

ESTIMATES OF OMC PCB

USAGE DURING 1950'S-1970'S

Total Usage

Year	Type	lbs	kg
1955	Not known	333,500	151,400
1956	Not known	749,600	340,300
1957	Not known	485,600	220,500
1958	Not known	531,400	241,200
1959	F9	539,400	244,900
	A200	10,000	4,500
1960	F9	376,100	170,700
	A200	224,000	101,700
1961	F9	275,800	125,200
	A200	320,500	145,500
1962	A200	570,000	258,800
1963	A200	598,000	271,500
1964	A200	828,200	376,000
1965	A200	752,300	341,500
1966	A200	709,700	322,200
1967	A200	851,300	386,500
1968	A200	1,390,700	631,400
1969	A200	1,123,900	510,200
1970	A200	914,200	415,000
	A-200B (Terphenyl)	10,800	4,900
1971	A200	78,700	35,700
	A-200B (Terphenyl)	923,600	419,300
1972	A-200B (" ")	1,002,400	455,100

Total of F9, A200 & Unknown	11,662,300	5,294,700
Total of F9, A200 w/o 1955-58	9,562,300	4,341,300
Average for 1955-1970 =	724,000 lb/yr	328,700 kg/yr.

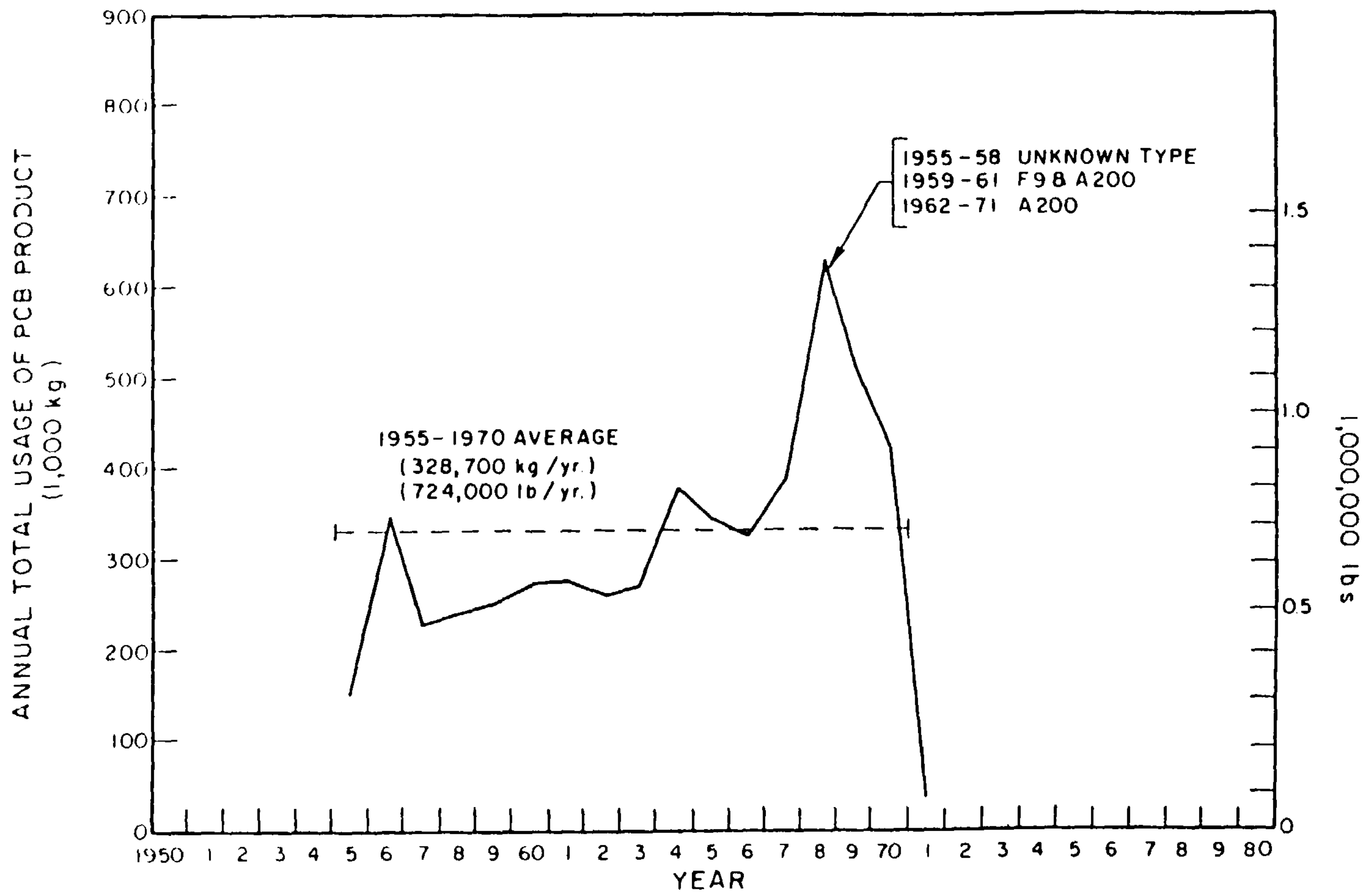


Figure 53. Annual total usage of PCB product (1955-1971)

the Ditch to be due to a discharge into segment 2 (the crescent), then the relative contribution to the total load to the lake can be estimated. In the Ditch calculation, it was estimated that 71% of the amount discharged was deposited in the sediment while 24% was discharged to the Lake. For the Harbor, the estimated percentages are 62% to the sediment and 38% to the Lake. It should be stressed again that these estimates are approximate only and may vary considerably depending on the frequency of various storm events and the frequency of bottom scouring of sediment and release of PCB.

Figure 54 shows the range of discharge to Lake Michigan of the PCB load to the Ditch-Harbor System. For example, if the PCB discharge to the Harbor is assessed at 70% of the total to the Harbor and the Ditch (the entire system), then about 35% of the total load would enter the Lake. The total load line covers the percentages between the 29% and 38% points. Thus no matter what the splitting of the load between Ditch and Harbor, the load to the Lake cannot exceed 38% and cannot be less than 29% of the total load. The slope of the total load line however indicates the sensitivity of the load to the Lake to the splitting of the load. For example, if the line of the total load is parallel to the horizontal axis there would be only one possible value for the load to the Lake no matter what the splitting of the total load between Ditch and Harbor might be.

The necessary pieces of information needed to arrive at an estimate of the PCB product loss to the Harbor-Ditch complex and Lake Michigan as a fraction of the total PCB product have now been developed and are listed in Table VII.

The calculation proceeds as follows. For either the North Ditch or the Harbor, the discharged load is computed as

PCB Product Loss Load to Harbor/Ditch =

$$\frac{\text{PCB mass in sediment of Harbor/Ditch}}{\text{Fraction transferred to Harbor/Ditch}}$$

PCB discharge to Lake from Harbor/Ditch = PCB Discharge to Harbor/Ditch - PCB Mass in sediment of Harbor/Ditch

% of Use Discharged to Harbor/Ditch =

$$\frac{\text{PCB Product Loss Load to Harbor/Ditch}}{\text{Total PCB Product Use}}$$

An example of the calculation is given using the Ditch. The "best estimate" for the PCB in the sediment is 277,363 kg. It is estimated that about 71% of any load to the Ditch is transferred

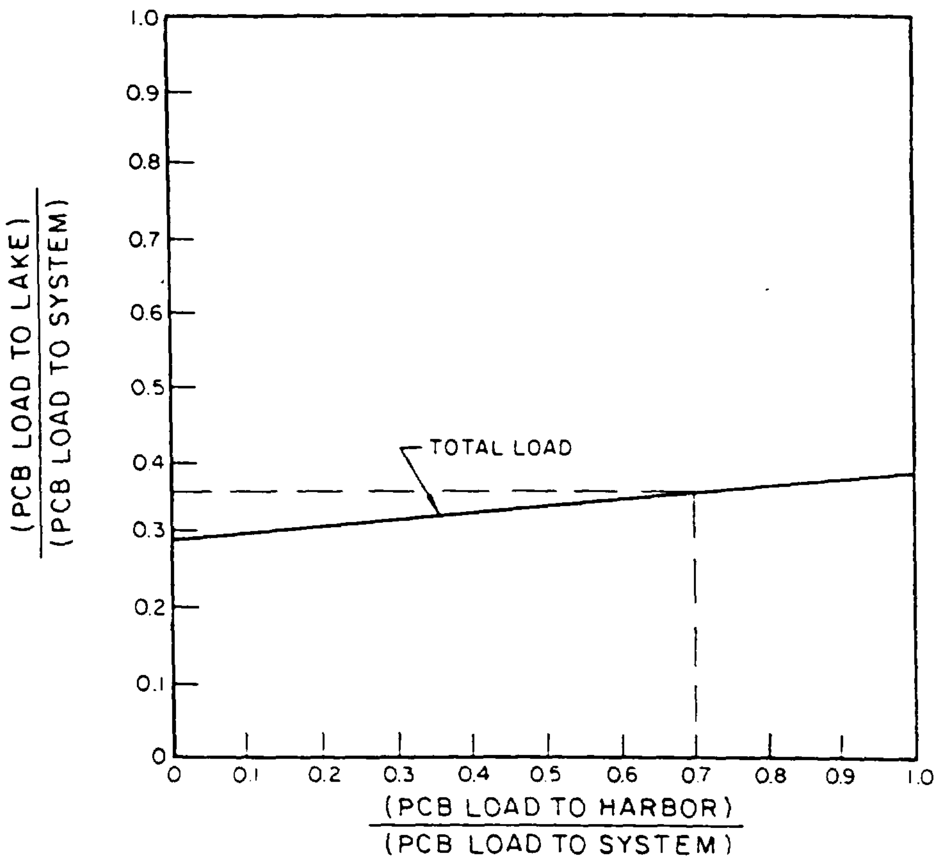


Figure 54. Sensitivity of system load to Lake Michigan on load to Waukegan Harbor

TABLE VII

SUMMARY OF INFORMATION FOR ESTIMATE OF DISCHARGED LOAD AS % OF USE

Information	Source	Values	
1. Total PCB Product Use	Plant Records	5,300,000 kg;	(11,660,000 lbs)
2. PCB mass in Harbor sediment (Best, High, Low estimates)	Field data analysis & calculation	207,100 kg; 343,300 kg; 75,600 kg;	(456,200 lbs) (756,200 lbs) (166,800 lbs)
3. PCB mass in North Ditch sediments (Best, High, Low sediment)	Field data analysis & calculation	277,400 kg; 527,500 kg; 49,800 kg;	(611,000 lbs) (1,161,900 lbs) (109,700 lbs)
4. Harbor transfer parameters Fraction transferred to lake Fraction transferred to sed (Harbor)	Harbor Math. Model calibrated to field data	 .38 .62	
5. North Ditch transfer parameters Fraction transferred to lake Fraction transferred to sed (Ditch)	North Ditch Math. Model calibrated to field data	 .29 .71	
6. Duration	Plant records	16 yrs.	

to the sediment and 29% is transferred to the Lake. Then the 277,360 kg in the sediment represents a

$$\text{PCB Product Loss to Ditch} = \frac{277{,}360 \text{ kg}}{.71} = 390{,}650 \text{ kg} = 10{,}160 \text{ kg/yr for 16 years.}$$

$$\text{Load from Ditch to Lake} = (390{,}650-277{,}360)\text{ kg} = 113{,}290 \text{ kg}$$

Similarly, using the estimates for the PCB in the Harbor sediments, the PCB product loss load to the Harbor can be calculated. The results of these calculations are shown on Figures 55, 56 and 57. A summary of the product loss and total flux to Lake Michigan are given in Table VIII from which it follows that the PCB product loss to product loss to the Harbor-Ditch system is estimated at about 14% of the total usage of PCB product purchased. It amounts to about 725,000 kg or an average rate of 45,300 kg/yr for 16 years. Depending on the range in the estimate of the PCB mass in the sediment, the estimated percent discharged is from 4% to 24%. It also follows from Figure 55 that during the discharge of PCB product, about 5% of the total PCB product purchased entered Lake Michigan. The discharge to the lake is estimated at a total of 240,220 kg or an average rate of 15,000 kg/yr for 16 years. The range in the estimates should be noted where an approximate order of magnitude variation in the estimate is calculated. This is a direct consequence of the uncertainty in the estimate of the PCB mass in the sediment.

The estimated flux of 15,000 kg/yr (33,000 lb/yr) to the lake under the "best estimate" during the PCB product usage can be contrasted to the total present flux from the Harbor/Ditch complex at about 10-20 kg/yr (22-44 lb/yr). The comparison indicates that during the time of PCB use, the discharge to the lake was probably at least 100-1000 times greater than at present.

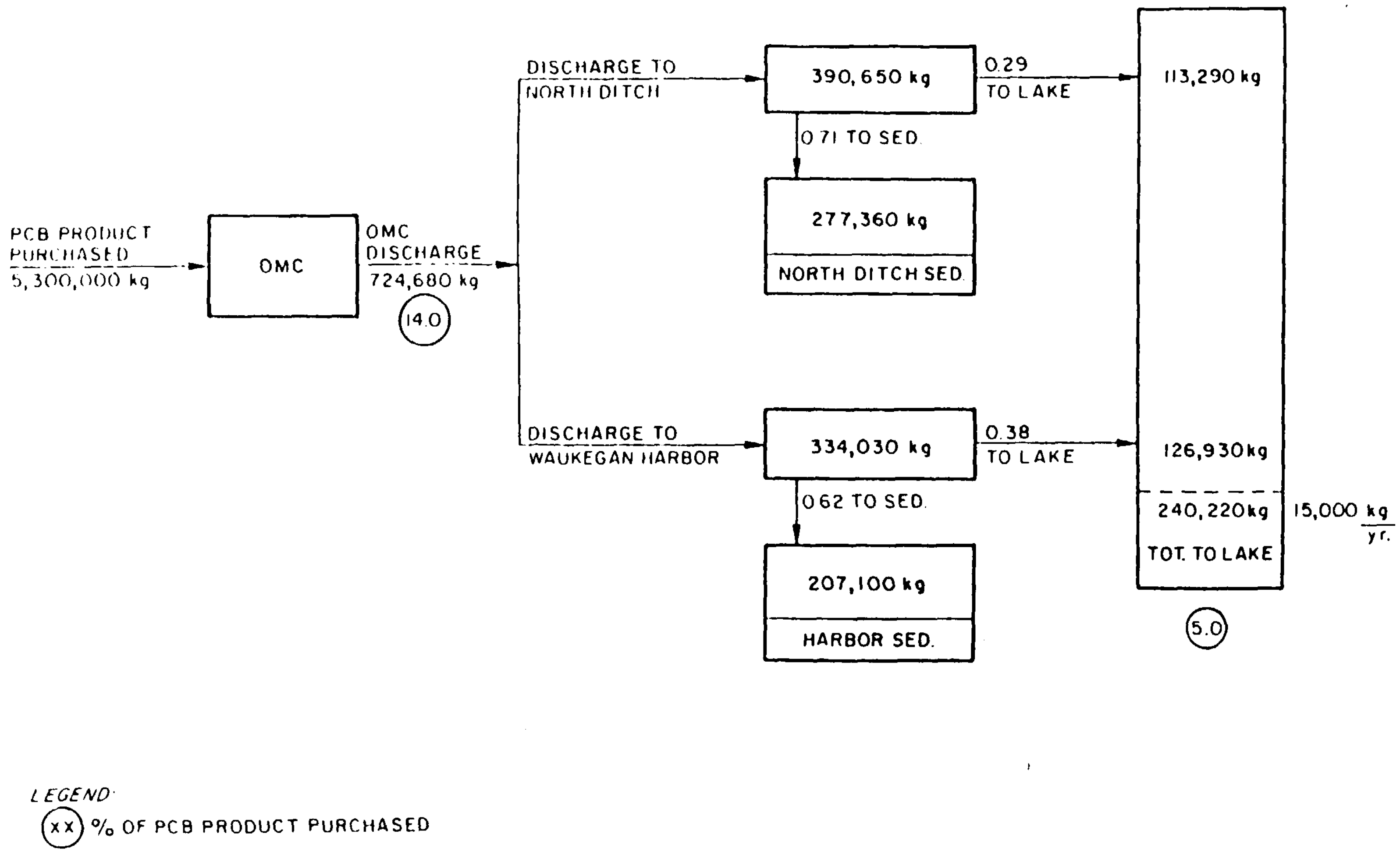


Figure 55. "Best estimate" of OMC discharge and resulting loads to Waukegan Harbor, North Ditch and Lake Michigan

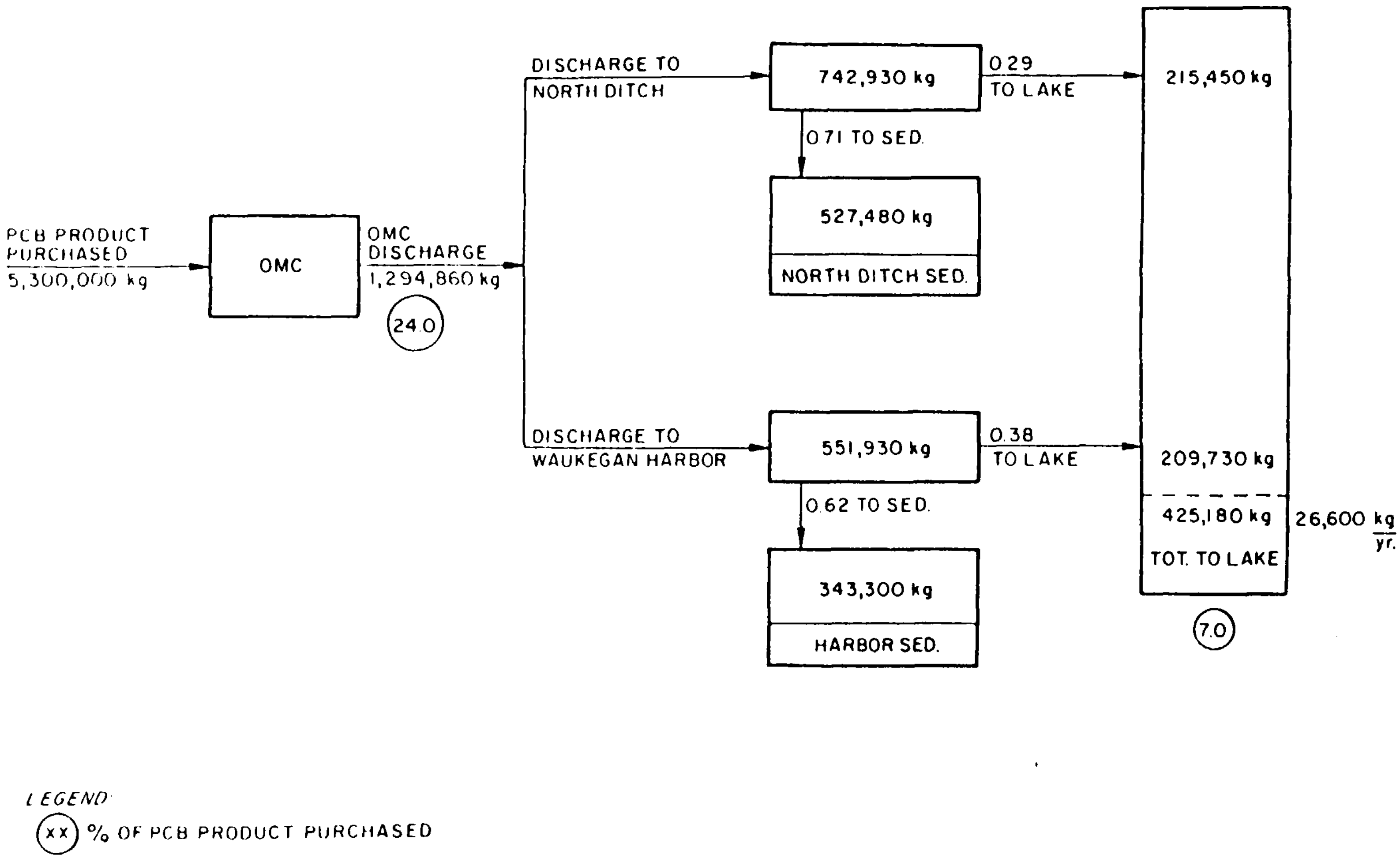


Figure 56. "High estimate" of OMC discharge and resulting loads to Waukegan Harbor, North Ditch and Lake Michigan

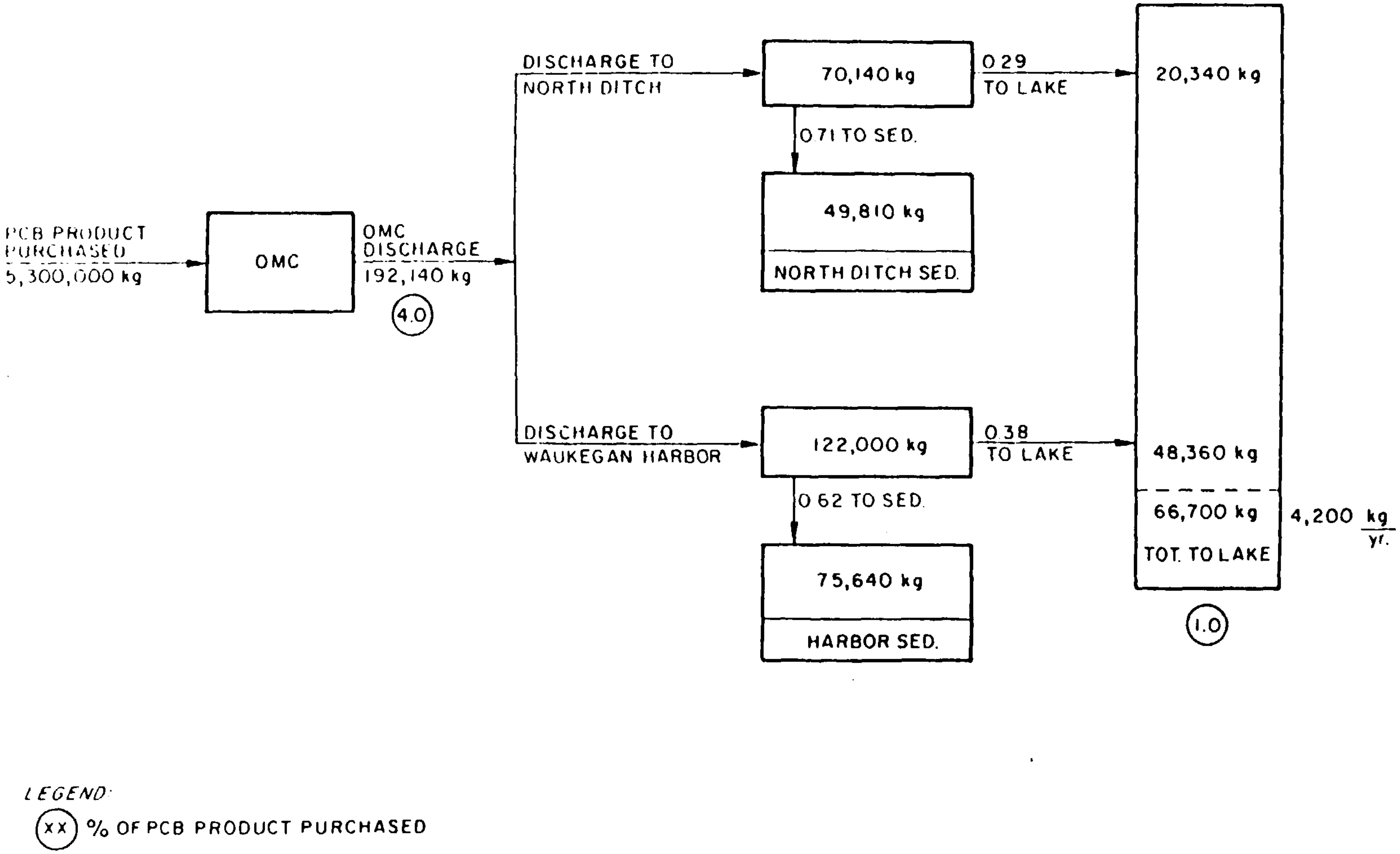


Figure 57. "Low estimate" of OMC discharge and resulting loads to Waukegan Harbor, North Ditch and Lake Michigan

TABLE VIII

SUMMARY OF ESTIMATES OF PRODUCT LOSS AND TOTAL FLUX TO LAKE MICHIGAN

	Sed. Mass PCB (kg)		Fraction Transferred to Sed.		PCB Product Loss (kg)		% of Total Usage Discharged to Harbor + Ditch	Total Flux to Lake Michigan (kg/yr)
	Harbor	Ditch	Harbor	Ditch	Harbor	Ditch		
Low	75,640	49,810	0.62	0.71	122,000	70,140	3.6	4,200
Best	207,100	277,360	0.62	0.71	334,030	390,650	14	15,000
High	343,300	527,480	0.62	0.71	551,930	742,930	24	26,600

SECTION 11

SIGNIFICANCE OF HARBOR/DITCH DISCHARGE TO LAKE MICHIGAN - PRESENT AND DURING USE OF PCB

It was indicated previously that the estimated present flux of PCB from the Harbor/Ditch system to Lake Michigan is about 10-20 kg/yr (22-44 lb/yr). At times, various storm events may increase this total by another 5-10 kg. In the past, however, based on the calculations presented in Section 11, the discharge from the Harbor/Ditch complex to the Lake may have ranged from about 4000 kg/yr to about 27,000 kg/yr. It is important to place these estimates of past and present discharges into perspective by comparing the input discharge to other sources of PCB into Lake Michigan.

Various estimates of the present total PCB discharge to the whole of Lake Michigan have been made (e.g., Murphy and Rzeszutho, 1978). The estimates depend principally on the range of PCB assumed for precipitation to the Lake. Murphy and Rzeszutho (1978) give a range of 50-100 ng/l in precipitation and indicate that approximately 50% of the PCBs is in the form of the lower Aroclors such as 1242. Strachan and Huneault (1979) reported a mean value of 21 ng/l from measurement of total PCB concentration in precipitation in the Great Lakes area, not including Lake Michigan. For a range of concentration of 20-100 ng/l, the PCB load from precipitation to Lake Michigan is about 900 to 4600 kg/yr (2000-10,100 lb/yr). Additional inputs from dry deposition and tributaries to the Lake are estimated to account for about 500-1000 kg/yr. The total present load therefore to Lake Michigan is about 1400-5600 kg/yr of total PCB. If it is assumed that about 50% of the precipitation load is in the form of the lower Aroclors then the present input of those Aroclors to Lake Michigan from precipitation above is about 450 to 2300 kg/yr. A comparison of these ranges to the past and present inputs is shown in Figure 58.

The comparison indicates that the present flux from the Harbor/Ditch complex represents less than 1%-2% of the total PCB load to the entire Lake. If the comparison is made to the lower Aroclor in the precipitation, the present flux represents about 1%-6%. The present input is therefore not a significant percent of the present total load to the Lake. It should be noted however, that the comparison is to the whole of Lake Michigan and that the present flux is significant relative to the Harbor itself and to the resident fish and does influence a region outside of the Harbor mouth (see Figure 43).

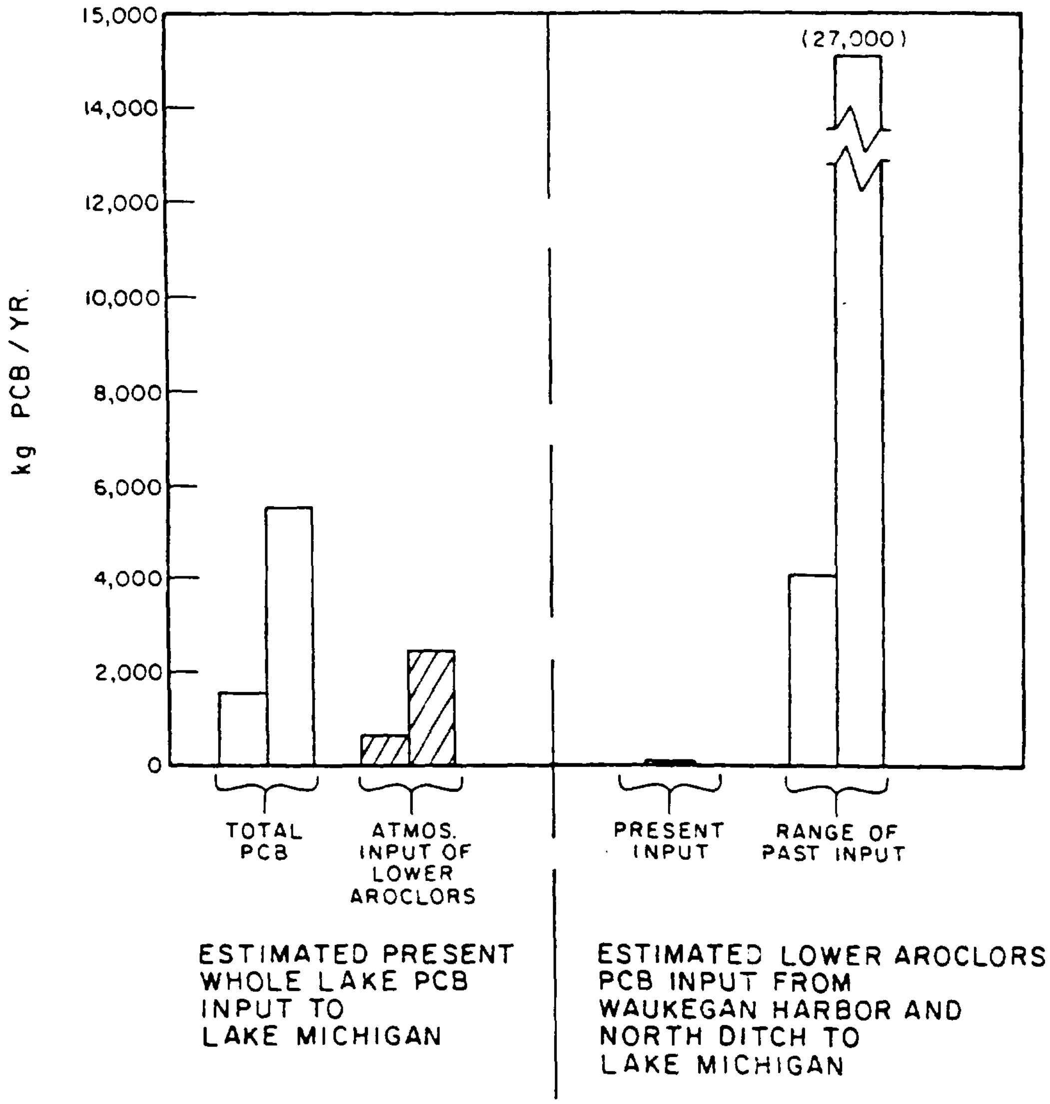


Figure 58. Comparison of Past and Present Waukegan Harbor/North Ditch Inputs to Present/Inputs to Lake Michigan

In the past, however, when PCBs were used, the estimated input from the Harbor/Ditch system may have greatly exceeded all other sources to Lake Michigan. For the estimated past input conditions, the range of 4000-27,000 kg/yr is substantially greater than the range of present input of total PCB of 1400-5600 kg/yr. One concludes form this coparison that it appears that the major input of PCBs from Waukegan Harbor and the North Ditch to Lake Michigan occurred during the time of PCB usage by the OMC plant. When purchases ceased and discharges to the Harbor/Ditch were discontinued, the mass flux of PCB to the Lake, as a whole, dropped significantly.

In order to assess the significance of the past discharges of PCBs to Lake Michigan, a similuation analysis was conducted using a model of the Lake. This latter model was constructed under other research work that incorporates phenomena similar to the model discussed herein and is reported on in Thomann (1980b). The whole Lake Michigan model was calibrated to suspended solids and plutonium-239 data. Details are given in Thomann (1980b).

Figure 59 shows the assumed input load of 15,000 kg/yr beginning in 1955 and continuing to 1971. This load represents the best estimate of the discharge from the Harbor/Ditch system as discussed in Section 11. Figure 60 indicates the range of the calculated response based on whether a) the loss of PCB from the water column is due to settling only, (upper limit) or b) the loss of PCB also includes loss due to evaporation or non-desorbably PCB (lower limit). Peak concentrations are reached in 1970 where the calculated range in the whole lake PCB concentration due to 15,000 kg/yr is from about 7 to 15 ng/l. Following cessation of the input, the water concentration of the Lake is calculated to decline to 0.1-2.0 ng/l.

The significance of the 7-15 ng/l range can be assessed by comparing this range to the additional concentration that results from the other inputs to Lake Michigan. Considering these other inputs to be "background" at 1400-5600 kg/yr, the response under the settling only case is from 2-6 ng/l. It should however be noted inputs to Lake Michigan, on a whole lake basis, may have been greater or less than this value. Under the case of evaporation or non-desorbable PCB, the response due to the background load is from about 1-3 ng/l. Figure 60 shows this latter case which indicates that during past discharges from Waukegan Harbor and North Ditch, the resulting PCB concentration may have been about 70-88% of the ambient total whole lake concentration. Under the upper limit, the range is 54-78%. Thus, about 50-90% of the concentration of PCB in 1970 in Lake Michigan is calculated to be due to the discharge from the Harbor/Ditch system. Now, one can make the very simple, but measurable and defensible assumption that the PCB body burden in

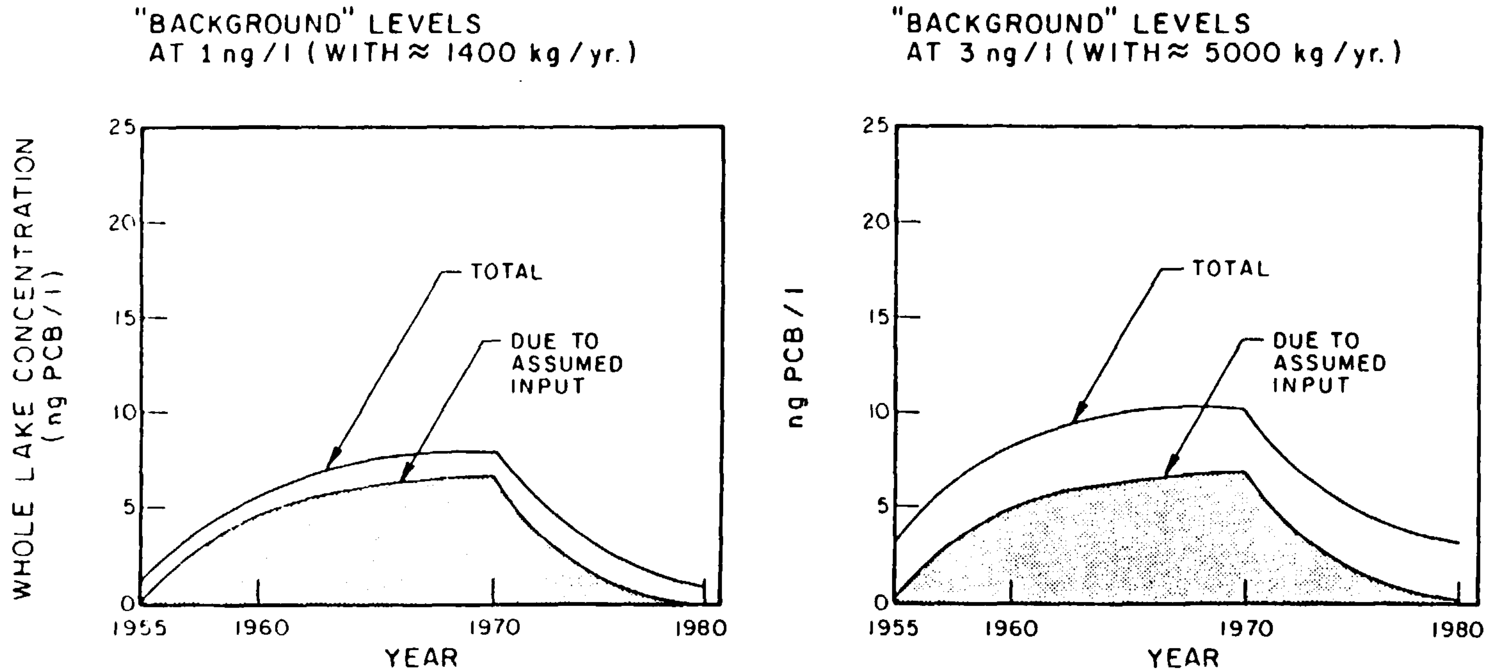


Figure 60. Comparison of calculated whole lake response to "Background" Levels of 1 ng/l and 3 ng/l

the top predator of Lake Michigan is directly proportional to the water concentration. Therefore, 50-90% of the PCB levels in lakefront in 1970-71, may have been due to the discharge from the Waukegan Harbor/North Ditch system.

In summary, this entire analysis indicates that relative to the whole of Lake Michigan the present flux from Waukegan Harbor and the North Dith of about 10-20 kg PCB/yr is small when compared to the total present load of 1400-5600 kg PCB/yr. The present flux however is considerably more significant on a local near-shore basis. The past flux during time of discharge may have ranged from 3 to 5 times the PCB input from other external sources. For an assumed time history of 15 years of flux at 15,000 kg/yr, the equilibrium water column response for Lake Michigan ranges from 7-15 ng/l at peak level in 1970. The past discharge from the Harbor and Ditch during use of PCB may have accounted for 50-90% of Lake Michigan water concentration at peak levels.

SECTION 12

SIGNIFICANCE OF THE REMOVAL OF HARBOR SEDIMENT

It was estimated that approximately 207,100 kilograms of total PCB are contained in the sediments of Waukegan Harbor. It is these PCB's, located primarily in Slip # 3 of the inner Harbor, which are the driving force for the PCB's entering Lake Michigan from the Harbor. Proposals to dredge Waukegan Harbor to remove contaminated sediments have been made. However, the extent to which dredging would be necessary, in terms of to what levels PCB's should be reduced, was unclear. The impact of dredging to various levels of PCB upon Harbor water column concentrations, and upon the PCB load to the Lake and, the impact upon the concentrations of PCB in resident fish species was not known.

The mathematical modeling framework, as outlined in previous sections, was applied to these questions. A series of simulations was performed in which the PCB levels contained in the sediments were reduced from the estimates of the present concentrations to 100 μg/g, 50 μg/g, 10 μg/g and 1 μg/g levels. The kinetic constants and parameters, Lake Michigan boundary concentrations, etc., were not changed from those used in the calibrations. The results of these simulations are shown in Figure 61 along with calculated present levels of total PCB.

The dredging of Harbor sediments to a level of 100 μg/g would reduce peak water column concentrations by approximately one order of magnitude. Reductions to the 50 μg/g or 1 μg/g levels would have significantly smaller impacts upon the reductions in water column concentrations in the inner Harbor and almost no impact on concentrations which would be observed at the entrance to the Harbor.

The net flux of total PCB on an annual basis to Lake Michigan under present conditions and as calculated for each of the dredging simulations are presented in Table IX.

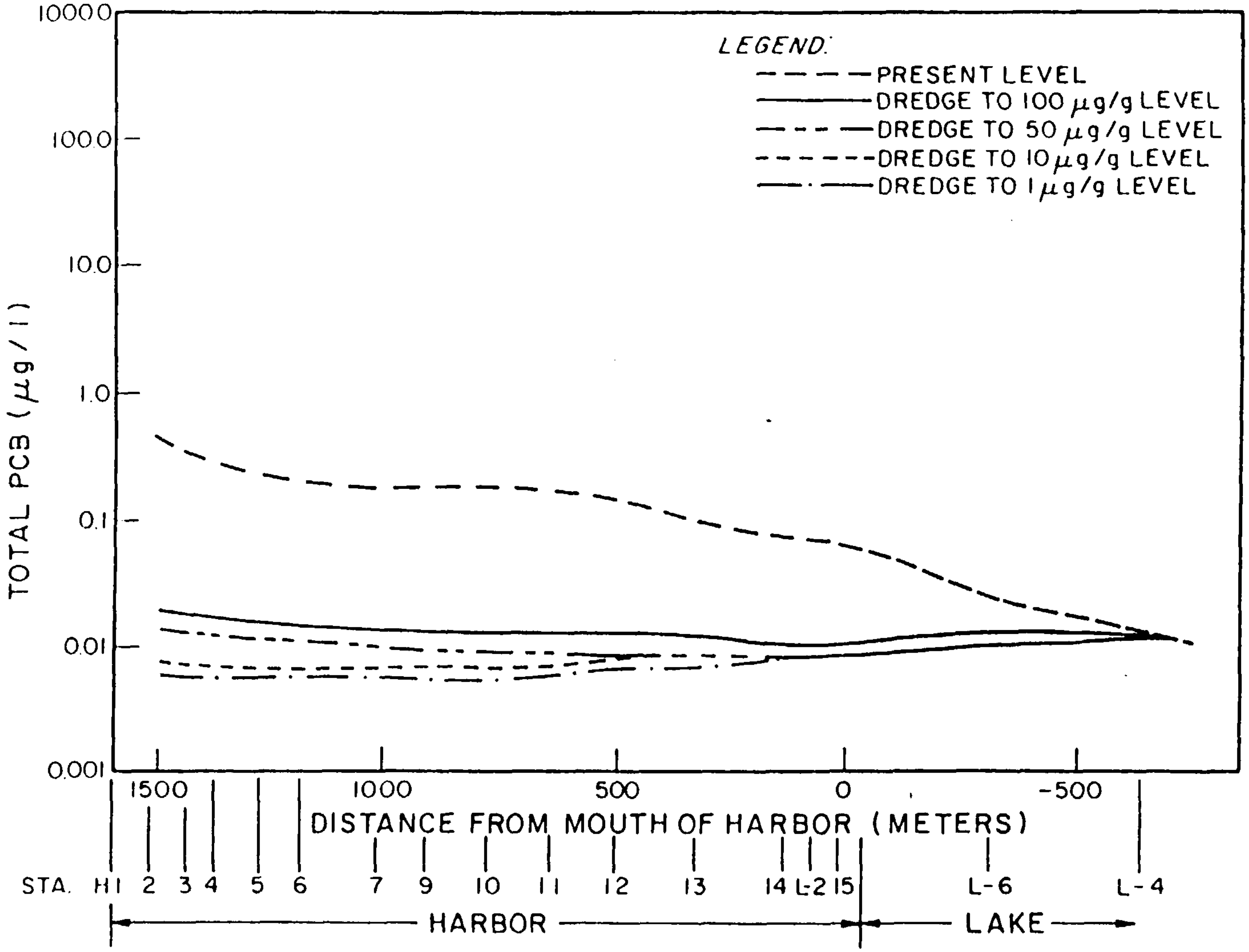


Figure 61. Estimates of the impact of dredging on PCB water column concentrations

TABLE IX

Harbor Sediment PCB Levels	Flux of Total PCB from Harbor to Lake Michigan
Present Level (No Action)	<10 kg/year
Dredged to 100 μg/g	-.3 kg/year
Dredged to 50 μg/g	-.4 kg/year
Dredged to 10 μg/g	-.43 kg/year
Dredged to 1 μg/g	-.45 kg/year

The estimated 10 kg/year which is presently entering Lake Michigan is eliminated by dredging the Harbor to the 100 μg/g level. At this level, concentrations in Lake Michigan are higher than those at the mouth of the Harbor. This is calculated to result in a net transfer of PCB into Waukegan Harbor. These are approximate calculations only and simply indicate that dredging to levels of approximately 10-100 μg/g would probably eliminate the present discharge of PCB from the Harbor to the Lake.

The estimation of the reduction in water column PCB concentrations as a result of dredging permits subsequent estimation of the expected reduction in the PCB concentration of any resident fish species. The calculation follows the general approach outlined earlier, namely that an approximate bio-accumulation factor of 630 μg/g per μg/l is reasonable. The dissolved PCB concentration calculated from the preceding analysis was therefore used together with this accumulation factor. The results are shown in Figure 62. Dredging to the 100 μg/g level is estimated to result in a significant decline in fish body burdens to less than 5 μg/g for all but the innermost 500 m of the Harbor. Dredging to the 10 μg/g sediment PCB level results in a further decline in fish PCB concentrations to about 3 μg/g for the entire Harbor. Additional removal of sediment to 1 μg/g does not result in any significant further reductions. In all cases, the resulting body burden, on a whole-body basis, is estimated to be above, but only slightly for the 1 μg/g case, the proposed FDA limit of 2 μg/g.

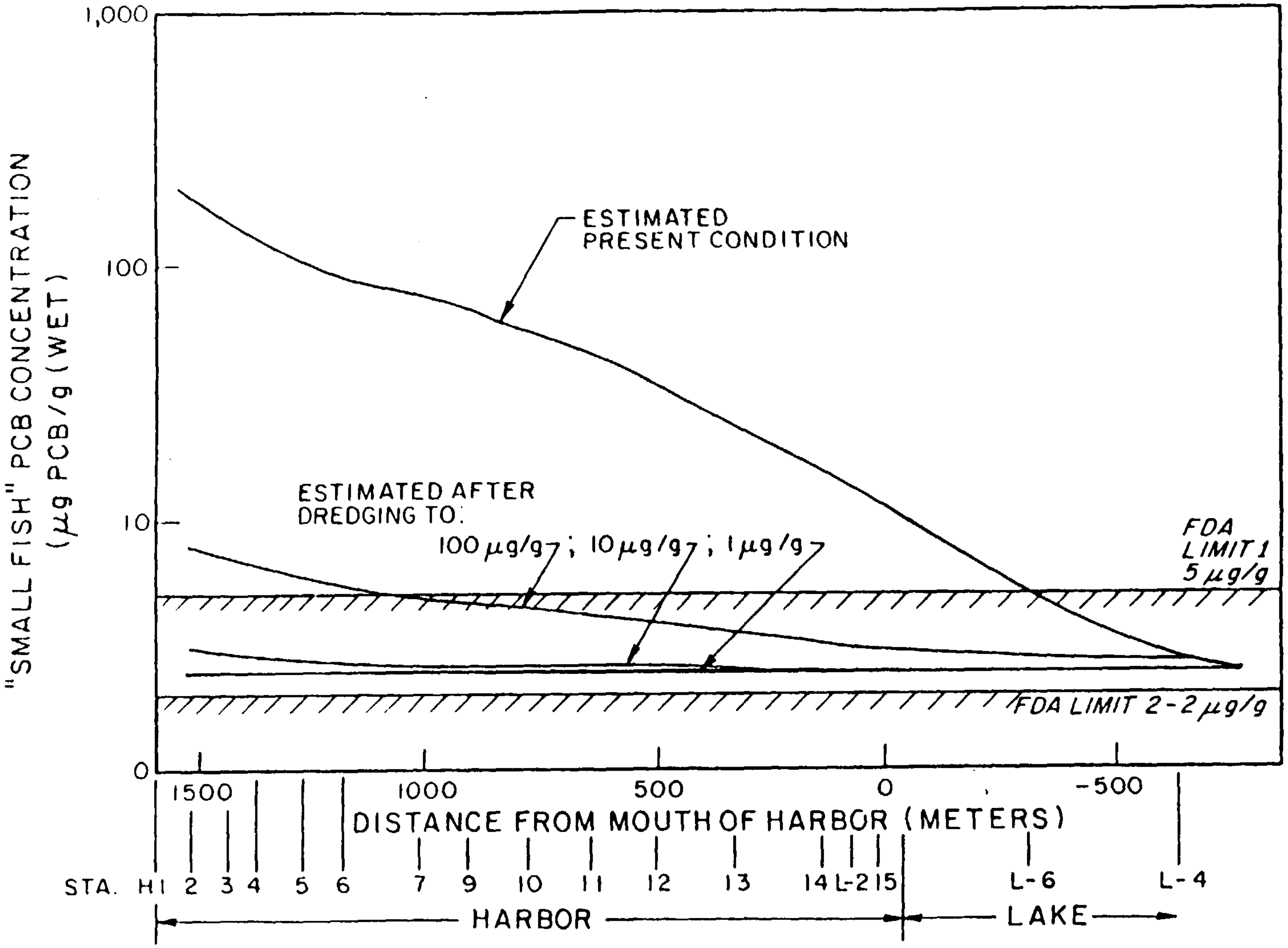


Figure 62. Estimated small fish PCB concentration after dredging to alternative sediment PCB concentrations

REFERENCES

1. Argonne National Laboratories, 1979. Final Report, 1979 Waukegan Harbor Studies, Performed for U.S.E.P.A., Region V.

2. Armstrong, D.E., 1979. Report on PCB's in sediment samples from Waukegan Harbor and Southern Lake Michigan. Prepared for U.S.E.P.A., Chicago, Ill. Water Chem. Lab., Univ. of Wisconsin, Madison, Wisconsin, 19 pp.

3. Battelle, Undated. Section 3, Site Description. From report on Waukegan Harbor. pp. 5-22.

4. ERG, 1979. Draft report, sampling and analysis of water and sediment. Samples taken from Waukegan Harbor before, during and after maintenance dredging. Performed for U.S.E.P.A., Region V on behalf of JRB Assoc., Inc., McLean, Va. by ERG, Bridgeview, Ill., 32 pp. and Appendix.

5. Hydroscience, Inc. 1978. Estimation of PCB reduction by remedial action on the Hudson River ecosystem. Prepared for the N.Y. State Department of Environmental Conservation.

6. IJC, 1978. Environmental management strategy for the Great Lakes. Final report to the IJC from the Int. Ref. Grp. on Great Lakes. Poll. from Land Use Act., IJC, Windsor, Ontario, 115 pp.

7. Linsley, R.K., et.al., 1958. Applied Hydrology. McGraw Hill Book Company, N.Y., N.Y. 340 pp.

8. Marion, B.B., 1979. The Waukegan PCB problem: How much public participation is enough? Presented at 22nd Conference on Great Lakes Res., Rochester, N.Y., 7 pp.

9. Mason & Hanger-Silas Mason Co. Inc., 1981. An Engineering Study for the Removal and Disposition of PCB contamination in the Waukegan Harbor and North Ditch at Waukegan, Illinois. Final Report to U.S.E.P.A. Region V, Chicago, Illinois, 152 pp and Appendices.

10. Murphy, T.J. and C.P. Rzeszutko, 1978. Polychlorinated biphenyls in precipitation in the Lake Michigan basin. EPA 600/3-78-071. Env. Res. Lab., Dubuth, Minn., 33 pp.

11. Noehre, A.W. and J.B., Graf. 1980. An estimate of sediment movement in North Ditch, Waukegan, Illinois. Administrative report. Prepared by the U.S.G. and U.S.E.P.A. 22 pp.

12. Parzen, E. 1960. Modern probability theory and its applications. J. Wiley & Sons, N.Y., N.Y. 464 pp.

13. Strachan, W.M.J. and H. Huneault, 1979. Polychlorinated biphenyls and pesticides in Great Lakes precipitation. J. Grt Lks Res. 5(1): 61-68.

14. Thomann, R.V., 1980a. Equilibrium model of microcontaminants in diverse aquatic food chains. To appear in Canadian Journal of Fisheries and Aquatic Sciences, March 1981.

15. Thomann, R.V., 1980b. Preliminary model of recovery of the Great Lakes following toxic substances pollution abatement. In manuscript.

16. Todd, D.K., 1970. The Water Encyclopedia. Water Information Center, Port Washington, N.Y., 559 pp.

17. Tofflemire, T.J. et al 1979. PCB in the Hudson River. Mapping: sediment sampling and data analysis. Tech. Report No. 57. N.Y. State, DEC, Albany, N.Y.. 32 pp.

18. U.S.E.P.A. Areawide Assessment Procedures Manual, 1976. Municipal Env. Res. Lab. ORD, U.S. EPA, EPA-600/9-76-014.

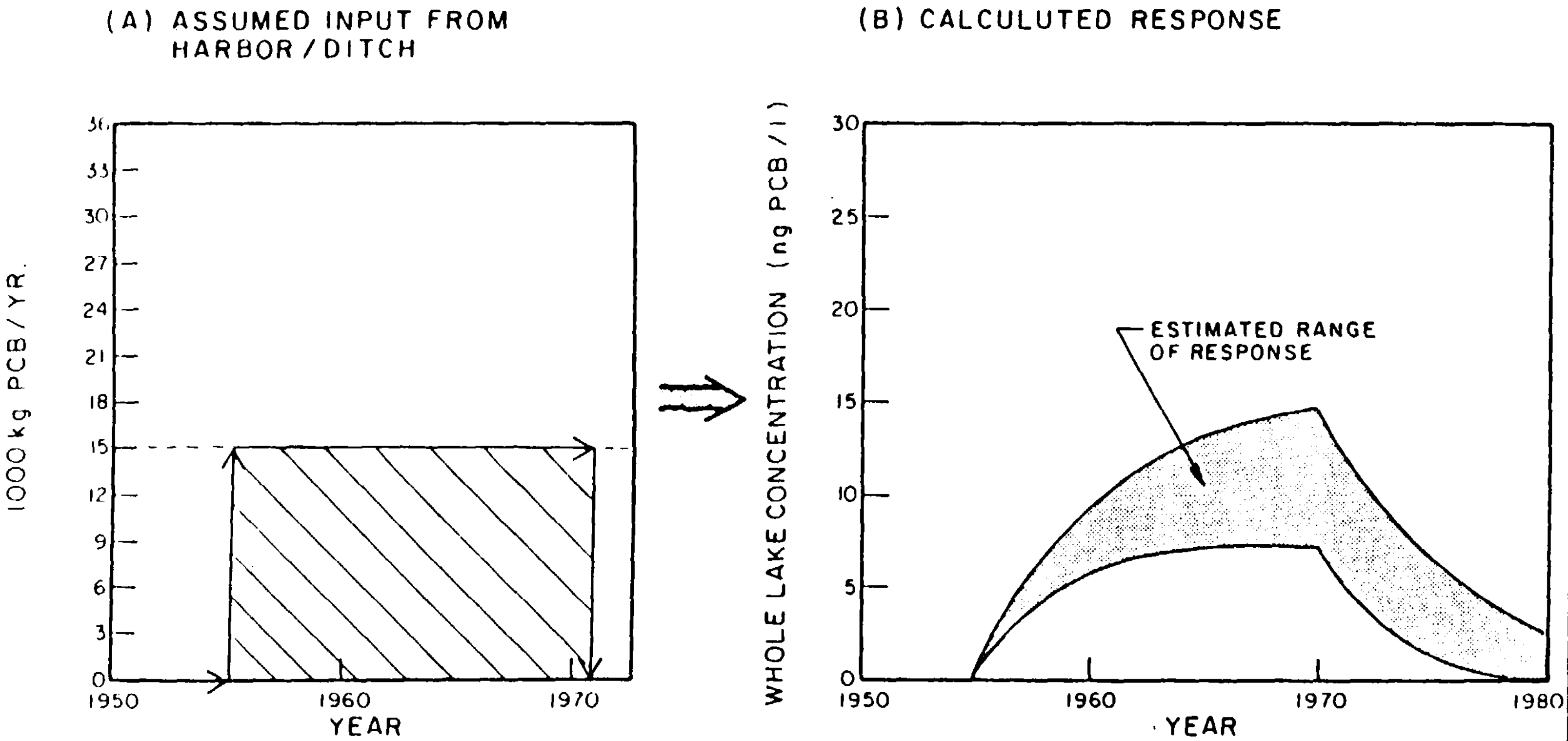


Figure 59. Long term response of Whole Lake Michigan to assumed PCB Input from Harbor/Ditch